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Challenges and opportunities for the control of Energy Storage Systems.

A focus on the Zinc-Air batteries.

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Abstract—The paper aims to review recent developments and points to the challenges and opportunities for the instrumentation, control and management technologies in relationship with the emergence of novel Energy Storage Systems. It exemplifies this trend with a technology that has received an increasing interest in recent studies: the Zinc-air batteries.

Index Terms—Control, mathematical modelling, identification, estimation

I. INTRODUCTION

The current decade came with added momentum in the research related to the energy storage systems in general with particular emphasis on the modules exploiting electrochemical principles of functioning.

This increased research activity was driven by multiple social needs and priorities. One of the most important aspects is the wide interest of the public in renewable energy sources which enables different subjects of research from the physical principles, to the harvesting, energy conversion and transmission. These topics are popular around the world in connection with the global increase in energy consumption and the current concerns related to the climate change and its irreversible impact. For example, the advances in photo-voltaic power production research and development¹ proved on large scales the capacity of harvesting the solar energy (by converting the solar radiation to heat and subsequently to different types of energy) but in the same time showed that solar radiation comes with a high irregularity and leads to voltage fluctuations in the power networks. These issues can be mitigated if the photo-voltaic plant is operated in conjunction with an energy storage system, (most commonly electrochemical batteries). Similarly, the wind energy may be limited due to the variability of weather conditions and this extends to the other renewable sources. To solve this problem, a reliable and cost-effective energy storage system is required, which, in addition, will have to be able to increase the stability

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¹See the project DESERTEC [1], officially launched in July 2009 enabled by the outstanding solar capacity in Africa.

and flexibility of power supply networks for both suppliers and consumers of electricity.

From another perspective, the introduction of storage elements may be seen as a game changer for the power grids which are considered classically as a "zero inventory supply chain". The storage elements will bring a novel controllability degree and eventually offer margins for real-time operation by using this lever on a safety and economical mixed optimization.

As an example in this respect, an increasing number of high-voltage transmission lines (63kV-90kV) reached the level of congestion due to the massive integration of renewable power generation sources [2]. The trend is increasing and will pursue its rapid development on the production side while the grid expansion plan will be too expensive to accommodate 100% of the nominal power. As such, the power curtailment continues to play its role for the congestion handling, but EES (Energy Storage Systems) and particularly batteries will become components of the grid. There are undergoing installation projects for batteries with 12 MW and 24 MWh energy rating (see for example the RINGO project in France [3]).

These large storage units have an important advantage in the control strategies for congestion management as long as their operation allows a response time of 1s for a transition from 0 to 12 MW for example. The predictive control finds in these framework its full interest as long as the pre-positioning of the batteries can enhance the remedial actions in congestion situations by energy storage during the high renewable generation and subsequent discharge when the renewable action decreases.

In the case of fault or outage, the lines can become overloaded and bring the entire network in a dangerous operation regime, the role of the battery being to charge and rapidly remove the overload.

While the opportunity offered by such large batteries are obvious, there are adjacent problems that need to be solved:

- Where to place the batteries in such a way such that the above mentioned capabilities are to be optimally used

by the control strategies. This problem relates to the theoretical notion of controllability in the case of large scale systems;

- How to dimension the batteries, knowing that their operation is concentrated on tackling congestion and faults that represent rare events and as such lead to an operation of the batteries at around 10% of the time.

In the present paper we aim to add to the above control-related aspects, a focus on a novel energy technology: the Zinc-air batteries. This energy storage systems is particularly promising due to the high specific energy density, which in practice reaches $700Wh/kg$, several times higher than the value for the popular lithium-ion technology [4]. In such systems, the flow of electric current occurs during the electrochemical reaction of zinc (anode) and oxygen (cathode). During battery discharge, the anode oxidizes, forming zincate, which then turns into zinc oxide, while an oxygen reduction reaction takes place at the cathode. Other metals, such as aluminum, lithium, potassium, sodium, etc., are also proposed to be used as the anode material. Zinc (Zn) is considered to be the most attractive in this regard, since it does not poison the environment, is safe, and can be reused after processing, is widespread in nature, and also has a relatively low cost. Due to these properties, the technology of zinc-air power sources has high potential and can find successful commercial applications as storage batteries for renewable energy sources, as well as for electric / hybrid vehicles.

However, the maturity of the technology (as it is the case for the lithium-ion batteries) builds on many aspects, such as the constituent materials of the battery, production processes, as well as a control/monitoring strategy. These last elements deserve a particular attention as they will operate the energy systems in real-time and consequently should be developed to a sufficiently reliable technological level. At the same time, the battery must meet modern standards of reliability and performance. Model-based analysis is an effective tool in the design and manufacture of power supplies, as well as an analysis of their behavior in various operating conditions. Consequently, an effective mathematical model is a key element for the development of Battery Management System (BMS).

The main function of the BMS is the ability to evaluate in real time the unmeasurable states of the power supply: charge (state of charge - SOC), health (state of health - SOH) and power (state of power - SOP), through the signals actually available for measuring: potential and current in the cell. Thus, the mathematical model underlying BMS must meet the requirements for accuracy and performance (in terms of prediction) for use in real time, and also have a structure convenient for identifying its parameters (adaptation, scalability). The model built on these principles will allow to study the dynamic characteristics of the power source and improve its performance by determining the optimal combination of input parameters and control strategy.

II. A BRIEF POSITIONING OF BATTERIES IN THE ENERGY STORAGE SYSTEMS LANDSCAPE

The story of the batteries in the stable and reproducible forms leading to an established technology can be traced back to 1859, to the French scientist Gaston Planté. It is interesting to see the actuality of the Planté's first studies who tried in his study "Storage of Electrical Energy" to deepen the understanding of the "the accumulation and transformation of the energy of voltaic battery by means of secondary currents". Even nowadays, the philosophy of the control engineering problems can be resumed by the same objectives.

After these early beginnings, the solutions for the energy storage varied in time and span a large spectrum of functioning principles according to the range of applications. One can recall, for example, the flywheels which are costly equipments which provide a relative low storage capacity but can be designed and implemented in various configurations and thus offer flexibility. Another safe and large scale deployed energy storage solution is the one based on hydro pumping which has the highest storage capacity at a low price. However, such solutions are conditioned geographically and come with a high environmental impact. Aside these classical alternatives which can be seen as extreme options in terms of the cost (flexibility)-capacity trade-off for storing the energy, there exist a variety of electro-chemical solutions known under the broad name of battery systems.

The construction of the batteries has a history of over 200 years and relies on different technologies. One can cite among the important classes those based on *NaS*, *lead-acid*, *flow batteries* and *Li-ion* to mention only the ones that can be encountered in configurations with diverse scales and mature solutions. Obviously the cost-capacity trade-off will differentiate those categories and orient their usage with respect to the applications.

In the case of *NaS*, the batteries have a high energy density and a long life cycle but they are penalized by the highly corrosive nature of the components and the fire hazards of the pure sodium. As such they are representing a solution of energy storage well-suited for the support of the electric grid, as for example for voltage regulation.

The *Li-ion* batteries are preferred for the home appliances and mobile electro-mechanical or communication solutions while lead batteries are known for their ability to deliver high instantaneous currents and the advantageous power-to-weight ratio. Finally the flow batteries are interesting for the high levels of power output and energy stored.

III. A MODEL-BASED PERSPECTIVE ON BATTERY SYSTEM OPERATION

According to the current trends, the coming decades will see the class of galvanic batteries becoming predominant among energy storage devices. Simulation based on mathematical modeling is a primary concern in designing and manufacturing a battery, and also acts as a tool for assessing conditions such as SOC (state of charge) and SOH (state of health) in

support of implementing real-time battery management systems. Hence, for precise control and monitoring, sufficiently accurate battery models are required, while simultaneously being efficient in terms of computational costs. Currently, the most common and developed types of electric batteries include lithium-ion, lead-acid and nickel-metal hybrid batteries [5]. In this regard, considerable attention is paid in the scientific literature to the issues of mathematical modeling and design of monitoring and control systems for power elements of these types [6], [7]. In turn, zinc-air power sources are mainly the subject of analysis of applied chemical research, the purpose of which is to model individual chemical processes inside the battery to determine the effect of intrinsic parameters on its characteristics [8]–[10].

A. Mathematical models for batteries

The most common mathematical modelling efforts can be divided into two groups: electrochemical models and models of equivalent electrical circuits. Also, in connection with the active development of intelligent technologies at present, a number of researchers identify a third category - the “black box” model.

Electrochemical models are usually focused on the fundamental, physical aspects that underline the operation of power supplies [11]. The electrochemical model is a numerical model consisting of nonlinear partial differential equations describing kinetics with high accuracy. They are useful in designing a battery, however, the complex structure of the model requires a difficult identification of parameters and makes them difficult to simulate/evaluate efficiently. This makes such models unsuitable for use in real-time control systems. The “black box” model or data-driven model is formed by training on experimental data using, for example, artificial neural networks. Since this approach does not imply the presence of state dynamic equations in the model, the accuracy of the simulation directly depends on both the quality and volume of the training data set, which in practice cannot always be guaranteed (see over-fitting problems).

Mathematical models of equivalent electrical equivalent circuits, due to their simplicity, are widely used in describing the behavior of various types of batteries, assessing the level of charge and monitoring their condition. An equivalent circuit is a circuit consisting of ideal components that together function in much the same way as a simulated system. The main elements of the circuit are a source of voltage, resistance and capacitance. There are several types of equivalent circuits, depending on which elements are used and what internal effects of the system need to be described. Classical equivalent circuits include internal resistance, Thevenin, RC models [12]–[14] and, regardless of the structure, are models with lumped parameters.

A basic scheme is presented in Figure 1 where the following notations are employed:

- OCV open circuit voltage
- I load current (charge or discharge)
- U_t terminal voltage

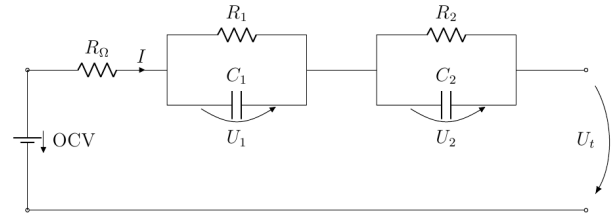


Fig. 1. Basic electric equivalent model

- R_1, R_2 polarization resistances
- C_1, C_2 polarization capacitances

and the relationships:

$$\begin{aligned}\dot{U}_1 &= -\frac{1}{R_1 C_1} U_1 + \frac{1}{C_1} I \\ \dot{U}_2 &= -\frac{1}{R_2 C_2} U_2 + \frac{1}{C_2} I \\ U_t &= OCV - U_1 - U_2 - R_\Omega I\end{aligned}$$

leading to an equivalent transfer function:

$$U_t(s) = OCV - \left(R_\Omega + \frac{R_1}{s R_1 C_1 + 1} + \frac{R_2}{s R_2 C_2 + 1} \right) I(s)$$

Models with lumped parameters are preferred for analysis, control, and optimization of power supplies, since in such approaches, the main objective is the global general characterization of the dynamics in terms of evolution of the output voltage, discharge current, temperature, and SOC, and rivals with respect to the concentration and the internal state of electro-chemical reactions in the battery.

According to the authors, the studies concentrate on different lumped parameters. A non-exhaustive list can be:

- SOC – state of charge is defined as a measures the quantity of charge of the battery

$$SOC(t) = \frac{1}{Q_0} \int_{-\infty}^t I(\tau) d\tau$$

and should be understood as a ratio between the remaining capacity and the nominal capacity

- SOE – state of energy, the product between capacity and OCV [15]
- SOP – state of power, the product between charge/discharge current and voltage
- RDT – remaining discharge time; it can be seen as the quantity of time for which the battery (at a desired discharge current) can sustain the desired terminal voltage [16]
- RCE – rate capacity effect; shows how the battery capacity depends on the charge/discharge profile [16]
- PRDT – predicted rate discharge time
- EMF – electromotive force; OCV is the steady state of the EMF and they are linked through a relation depending on temperature and aging [17]

However, it should be remembered that the mathematical model constructed using the equivalent circuit remain linear. In order to take into account the nonlinear effects that occur in real power sources, the dependence of the model parameters (resistance, capacity, voltage) on the state of charge, temperature, or other external factors that vary with time needs to be introduced whenever the modeling needs to cover the entire life-time and different operating regimes.

One of the popular approaches for handling the nonlinearity of the ECM is to hide it in the dependence between OCV and SOC. An empirical nonlinear relation proposed in [18] uses five terms whose parameters need to be identified:

$$OCV(SOC) = A_0 + A_1 SOC + A_2 \frac{1}{SOC} + A_3 \ln SOC + A_4 \ln(1 - SOC).$$

Other dependencies modeled by approximation polynomials are constructed from measurements, or using correspondence tables [19], [20]. It should be noted that the state of charge (SOC) is not a measurable indicator, various methods are used to determine its values, generally using estimations. These include methods based on information treatment based on battery parameters, Coulomb counting, methods based on data analysis, and methods based on estimations using dynamic models built using equivalent electrical circuits.

The methods of the first category directly measure the open circuit voltage at known values of the state of charge and the subsequent approximation of the profile of the discharge of the battery. However, each type of battery has its own signature related to the chemistry or the architecture. While determining the state of charge by the voltage curve performs well, for example, for a lead-acid battery (OCV(SoC) dependence is linear), zinc-air batteries have a substantially flat discharge curve, which makes this approach inapplicable. In addition, while the battery is under load, it is not possible to update SoC values in real time using OCV measurements. For these reasons, OCV-based SoC assessment is usually used as an additional or corrective method in the background of the real-time control.

Coulomb counting consists in calculating the integral of the instantaneous current value at the terminals to determine the charge given to the batteries. The disadvantage of this approach is the need to know the initial value of the state of charge, as well as the use of high-precision sensors in order to avoid the accumulation of measurement errors. It is also proposed to combine a method based on measuring stress without load with a Coulomb calculation to obtain the correct initial SOC value.

In order to reduce the uncertainties of the previously mentioned methods for estimating SoC, recently novel methods are introduced that introduce the state of charge into the number of phase variables of the dynamics model and then use one of the following observers to estimate its value: Luenberger [20], sliding mode (SMO) [21], Kalman Advanced Filter (EKF) [18], Kalman Adaptive Advanced Filter (AEKF) [22] and H_∞ observer [19].

B. Control problems

Model-based methods are reliable in nature thanks to a feedback structure in which a state-space model containing SOC as one of the phase variables is used to represent the dynamic behavior of the battery. It is worth noting that the quality of the method depends on the accuracy of the system simulation. In addition, due to differences between power supplies, the parameters defined for one battery may not correspond to the parameters for another battery of the same type.

To resume, in battery energy management we are interested in maximizing performance and longevity. This optimization process requires a detailed understanding of the underlying electrochemistry. However, the electrochemical state variables are not directly measurable. At best, one can measure voltage, current, and temperature. Consequently, modeling and control are necessary to extract the full potential from batteries.

After the overview of the problems related with the model design presented in the previous subsection, one can describe from a control theory perspective [23], the batteries operation challenges by means of three important classes of problems:

- **Parameter Identification Problem:** use the measurements (current, voltage and temperature) to estimate uncertain parameters related to aging (charge capacity fade and impedance rise). The issues in addressing this problems come from the parametric modeling, nonlinear systems' identifiability, the need of persistent excitation.
- **State Estimation Problem:** use the measurements to estimate the electro-chemical variables of interest. The issues here are mainly related to the lack of complete observability and the model's nonlinearity.
- **Constrained Control Problem:** use the measurements to control the current such that critical electro-chemical variables are maintained within safe operating constraints.

IV. ZINC-AIR BATTERIES AND CONTROL ENGINEERING PROBLEMS

Zinc is used in different configurations for primary or secondary cells: Zinc-air, Zinc-carbon, Zinc-ion, Zinc-bromine, Zinc-cerium to mention only a few. Let us consider next the Zinc-air batteries as one of the technologies reporting active research results in the last years [10], [24], [25]. Such a system is considered promising for large-scale energy storage due to its high energy density at a fraction of the cost. Also, active research on the chemical related topics are currently focusing on the development of electrode materials.

In short, the Zinc-air battery stores and discharges energy via electrochemical reaction of zinc (Zn) and oxygen (O₂). Potassium hydroxide (KOH) solution is typically used as electrolyte. During discharge, Zn oxidation proceeds at anode. Zn reacts with hydroxide ions (OH⁻) to generate zincate ion (Zn(OH)₄²⁻) and electrons. Zn(OH)₄²⁻ is precipitated to zinc oxide (ZnO) when its concentration exceeds the saturation limit.

The electrons generated from anode are transferred to cathode via the external circuit. At cathode, O_2 from the atmosphere receives electrons and is converted to OH^- .

A. Mathematical modelling

Discharge profiles are available as open data [24], [26] and allow the construction of gray-box mathematical models by exploiting the structural properties, the trends of the discharge signals and concentrating the computational effort on the off-line parameter identification and online adaptation.

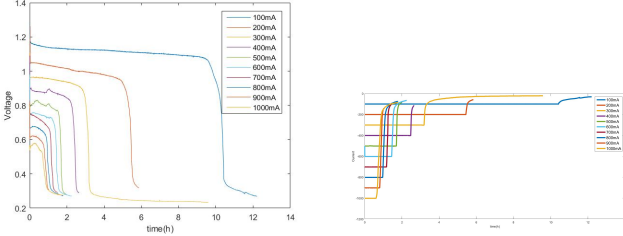


Fig. 2. Cell voltage and current at different (constant) discharge rates.

Using a modelling approach which involves a scalar state vector $z(k)$ denoting the SOC [27], one can concentrate on its evolution on the principles:

$$\begin{aligned} z(k+1) &= z(k) - \frac{\eta_s T_s}{C_n} u(k) + w(k), \\ y(k) &= K_0 - \frac{K_1}{z(k)} + K_3 \ln(z(k)) + K_4 \ln(1 - z(k)) \\ &\quad - Ru(k) + v(k) \end{aligned}$$

where $u(k)$ is the discharge current, $w(k)$ the disturbance and $y(k)$ is the cell's output voltage. The nonlinear dynamics can be enhanced with a linear subsystem, assimilated to an equivalent electrical circuit able to represent the fast transitory phenomena. The nonlinear feed-through takes into account the possible difference between the reference and the delivered discharge current:

$$\begin{aligned} x_1(k+1) &= x_1(k) + T_s f_1(x_1(k), u(k)) + w_1(k), \\ x_2(k+1) &= Ax_2(k) + B f_{21}(x_1(k), u(k)) + w_2(k), \\ y(k) &= Cx_2(k) + R f_1(x_1(k), u(k)) + v_k. \end{aligned} \quad (1)$$

The nonlinear function $f_{21}(x_1, u)$ depicts the dependence of the output voltage in terms of the state of charge and the discharge current. The results obtained based on interpolations between Boltzman approximation are depicted in Figure 3.

Interesting nonlinear phenomena have been observed as for example the non-linearity in the transitory, the flat discharge curve which lead to low observability indicators and other notions which deserve a mathematical formulation as for example the self-discharge susceptibility.

It is interesting to observe that reliable performance data and material properties are needed from experimental investigations and this is not always the case as long as the refuelable batteries are subject to a dispersion on the structure and organization of the zinc content which need to be considered in the corresponding mathematical model.

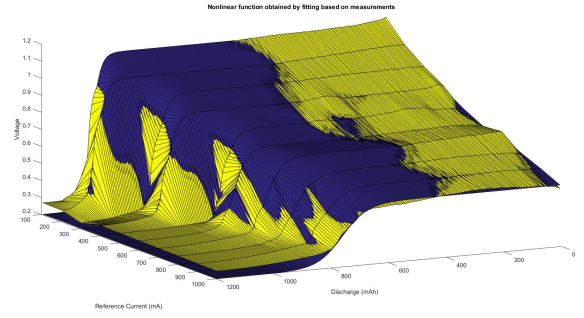


Fig. 3. Example of identification results with respect to SOC the nonlinearities.

B. Estimation problems

The state-of-charge concentrates the sensitive information about the operation of a battery. As it encapsulates a notion which is not directly measured, in some sense or another, it needs to be estimated based on real-time measurements. Its accuracy is important because errors in its measuring lead to infeasible discharging levels which adversely affect the battery performance and lifetime.

In control engineering terms, the OCV is the measured signal which is directly influenced by the SOC, and thus, at different SOC levels, the same discharge current leads to a different terminal voltage. This basic principle is exploited by the estimation mechanism starting from the basic idea of an inversion of the identified function $OCV(SOC)$. Such an approach can be both sensitive and non-robust in the case of Zinc-air batteries due to the flat discharge curve due to defective observability of the dynamics. The alternative is based on current counting and should be enhanced by means of persistent excitation with a rich discharge signal. All these elements can lead to a robust estimation in particular with respect to the refuelable Zinc-air batteries (both in terms of electrolyte and Zinc) which can suffer from different charging levels and arrangements of the components within the same geometry of the cell.

C. Fault detection and isolation

When discussing the long-term functioning of a battery, the focus moves from the state-of-charge to the state-of-health (SOH). This last notion deals with the ability of that battery to repeatedly provide its rated capacity over time. In general terms this covers the qualitative measure of the aging and degradation. In practice, the SOH deals with the monitoring the degradation of specific battery model parameters and is particularly efficient when a model-based approach can be employed. The principle is to trigger the fault-detection and identification by means of a residual signal involving the model-based predictions and the measured signals

When the SOH is jointly analysed with the SOC, the analysis is denoted "state-of-functioning" and deals with the fault detection and identification (FDI), followed by a estimation of the state of charge in the corresponding mode of functioning.

D. Real-time optimization-based operation

Once a reliable state estimation is implemented (supervised by a FDI monitoring block), the Zinc-air battery capabilities can be unleashed by opening the architecture and designing refuelable Zinc-air Batteries. Such battery structures provide novel degrees of freedom by the exchange of the chemical components of the electrochemical reaction with fresh elements. This research avenue is studied in the "Zinc and electrolyte regeneration" studies.

In a control engineering perspective, the objective can be stated as a reference tracking problem with respect to the exogenous discharge setpoints. The state estimation block need to monitor in real-time the state of charge and produce the residuals able to detect the entrance of the cell in a depletion stage. The feedback control has two levers: one on the adjustable quality of the tracking and on the other hand the regeneration signals on both the zinc and electrolyte side. It is worth to be noticed that the re-circulation of the electrolyte can help producing punctually high discharge intensity.

On the long run, the integration of the model-based predictive capabilities will allow an optimal operation in the sense of a receding horizon optimization and to monitor the functioning according to predefined discharge reference signals (patterns). The region of optimal performance will be the region where the cell can be maintained in nominal functioning by countering through control reconfiguration the depletion, despite disturbances and uncertainties.

V. CONCLUSION

The paper recalled the interest of energy storage systems in recent energy related applications. A short review of the modelling approaches needed for the design of control modules was provided and the particular case of the Zinc-air batteries was described as a particular example of the active developments in the field.

VI. ACKNOWLEDGEMENT

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