Wind Turbine and Electrochemical Based Storage Modeling and Integrated Control Strategies to Improve Renewable Energy Integration in the Grid

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UNIVERSITY OF GENOVA
Department of Naval and Electrical Engineering
Intelligent Electrical Energy Systems Laboratory

XXIII CYCLE OF DOCTORATE IN ELECTRICAL ENGINEERING
THESIS FOR THE DEGREE OF PHILOSOPHY DOCTOR

WIND TURBINE AND ELECTROCHEMICAL BASED STORAGE
MODELING AND INTEGRATED CONTROL STRATEGIES
TO IMPROVE RENEWABLE ENERGY INTEGRATION IN THE GRID

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March 2011
FOREWORD

I have always been fascinated by the electrical world since I have written, with my father help, my first essay for the primary school final exam, about the power plants typologies. Wind energy also catches my interest and when I was a child I realized a tiny homemade wind turbine.

By growing up I matured an environmentalist spirit, I got aware that our life style would not be sustainable in the long term. I decided to mate this attitude with my power plants interest and thus on 2001 I started the course in electrical engineering at the University of Genova.

Prof. Stefano Massucco gave me the chance to increase my knowledge of the power systems world by the PhD. Thanks to the participation to several research projects in collaboration with the ENEL Research Centre of Pisa and to the foreign experience in the Irish TSO, EirGrid, I had the chance to both study and work not only in the wind turbines world but also with the other renewable and conventional technologies. Thanks also to the collaboration and the fruitful discussions with my laboratory colleagues (especially Federico Silvestro and Samuele Grillo), I have acquired wide spectrum knowledge of the power systems and I have learned to master some powerful and useful technical software such as DigSILENT and Matlab-Simulink.

Despite my main interest is still on the wind, in this thesis I wanted to focus my efforts not only in the description and in the implementation of wind turbine models (on which a huge amount of work has been done worldwide) but also of storage system models, which could represent a powerful ally for the massive spread of the wind power.

I can certainly state that these years have been full of satisfactions and full of work as well! Now that my PhD is almost finished I’m still more resolved to deepen these topics and to further discover this fascinating and complex world. The way of the Power Systems is open!

Genova,
February 2011
Spero che i posteri mi giudicheranno con benevolenza, non solo per le cose che ho spiegato, ma anche per quelle che ho intenzionalmente omesso, così da lasciare ad altri il piacere della scoperta.

I hope that posterity will judge me with kindness, not only for the things that I have explained, but also for those I have intentionally omitted, so as to leave to others the joy of discovery.

- René Descartes
ABSTRACT

The aim of this thesis is to study and to describe the main dynamics that characterizes a wind farm composed by five full converter wind turbines and two different electrochemical storage technologies and to develop models, in the Matlab-Simulink simulation environment, for implementing integrated control strategies of the whole resulting system in order to evaluate the benefits that storage can provide.

Chapter 1 provides an analysis of the future drives in power systems and highlights the interest for the integration of the non-dispatchable renewable sources, as the wind energy. The presence of storage systems, in fact, could allow a better management of the electric system granting the full exploitation of renewable energy sources. The first step is therefore to study the single models to gain a better comprehension of the different dynamics implemented. The models are characterized from an electro-mechanical and an electro-chemical perspective and the time horizon of the studies ranges from minutes to hours in order to appreciate both the quickly changing wind dynamics and the slowly variability typical of the battery thermal dynamics.

Thus, in Chapter 2, the proposed wind turbine model is analyzed. It provides: an analysis of the aerodynamic behaviour of the rotor including the pitch control system, the shaft dynamic and the maximum power tracking control. Moreover an analysis of the wind speed profiles, one for each machine, used to feed the turbines is done and the turbine models are tested by means of these turbulent wind speed profiles.

Chapter 3 presents the developed storage models. These models are suited for electrical studies and they include: the state-of-charge behaviour, the electrochemical equivalent circuit, the thermal characterization and the protection and limitation systems. Two different storage technologies are chosen: one belonging to the Redox Flow group, the Vanadium Redox Flow Battery (also known as VRB™) and the other one belonging to the high temperature batteries, the Sodium Nickel Chloride (also known as ZEBRA™). The storage systems are tested by means of charge/discharge cycles, with different degree of intensity, to characterize their performances.

Hence, the main idea is to control the battery charging and discharging phases in order to control the whole plant output.

Therefore, in Chapter 4, different control strategies are analyzed. Different tasks are performed, the duties analyzed range from short-term fluctuation levelling and power quality improvement to generation shifting.

At last Chapter 5 reports the conclusions and the future research perspective.

The bibliography and the list of works published during the PhD are reported at the end of the manuscript.
SOMMARIO

Scopo della presente tesi è di studiare e descrivere le principali dinamiche che caratterizzano un parco eolico composto di cinque turbine (Full Converter) e due diverse tecnologie di accumulo elettrochimico e di sviluppare, in ambiente Matlab-Simulink, strategie di controllo integrate dell’intero impianto al fine di descrivere i benefici che l’accumulo può fornire.

Il Capitolo 1 propone un’analisi delle principali tematiche di ricerca relative ai Sistemi Elettrici ed evidenzia l’interesse sull’integrazione di generazione rinnovabile non-dispacciabile, come quella eolica. La presenza di sistemi di accumulo potrebbe, infatti, permettere una migliore gestione del Sistema Elettrico permettendo la piena utilizzazione delle risorse rinnovabili. Il primo passo è quindi quello di studiare i singoli modelli al fine di analizzare al meglio le differenti dinamiche implementate. I modelli sono caratterizzati da un punto di vista elettromeccanico ed elettrochimico e l’orizzonte temporale degli studi spazia da pochi minuti a parecchie ore, al fine di apprezzare sia le rapidamente variabili dinamiche tipiche del vento che quelle più lente caratteristiche delle dinamiche termiche dell’accumulo.

Perciò, nel Capitolo 2, è analizzato il modello della turbina eolica proposta, che include: un’analisi del comportamento aerodinamico del rotore comprensivo del sistema di controllo delle pale, la dinamica dell’albero di rotazione e il controllo di inseguimento di massima potenza. Inoltre viene effettuata un’analisi dei profili di vento impiegati, uno per ogni macchina, e i modelli delle turbine sono testati attraverso questi profili di vento turbolento.

Il Capitolo 3 riporta i modelli di accumulo sviluppati. Questi modelli sono calibrati per studi di tipo elettrico e implementano: il comportamento dello stato di carica, il circuito elettrochimico equivalente, la caratterizzazione termica e i sistemi di protezione e limitazione. Due differenti tecnologie di accumulo sono state scelte: la prima, appartenente al gruppo delle Redox Flow, è la Vanadium Redox Flow (nota anche col nome di VRB™); la seconda, appartenente alla famiglia delle batterie calde, è la Sodium Nickel Chloride (nota anche col nome di ZEBRA™). I sistemi di accumulo sono testati in risposta a cicli di carica/scarica, con differenti gradi d’intensità, al fine di caratterizzarne le prestazioni. Quindi, la principale idea è di controllare le fasi di carica e scarica delle batterie al fine di controllare la produzione dell’intero impianto.

Pertanto, nel Capitolo 4, sono analizzate differenti strategie di controllo e missioni test. Le applicazioni studiate vanno dallo spianamento delle fluttuazioni di potenza e miglioramento della Power Quality allo spostamento della generazione.

Infine il Capitolo 5 riporta le conclusioni e le possibili future ricerche.

La bibliografia e la lista dei lavori pubblicati nel corso del dottorato di ricerca sono riportati al termine del manoscritto.
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>RES:</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>TSO:</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>DSO:</td>
<td>Distribution System Operator</td>
</tr>
<tr>
<td>AGC:</td>
<td>Automatic Generation Control</td>
</tr>
<tr>
<td>AVR:</td>
<td>Automatic Voltage Regulator</td>
</tr>
<tr>
<td>PSS:</td>
<td>Power System Stabilizer</td>
</tr>
<tr>
<td>STATCOM:</td>
<td>Static Compensator</td>
</tr>
<tr>
<td>T&amp;D:</td>
<td>Transmission and Distribution</td>
</tr>
<tr>
<td>WT:</td>
<td>Wind Turbine</td>
</tr>
<tr>
<td>DFIG:</td>
<td>Doubly Fed Induction Generator</td>
</tr>
<tr>
<td>SCIM:</td>
<td>Squirrel Cage Induction Machine</td>
</tr>
<tr>
<td>WRIM:</td>
<td>Wound Rotor Induction Machine</td>
</tr>
<tr>
<td>TSR:</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>MPT:</td>
<td>Maximum Power Tracking</td>
</tr>
<tr>
<td>PI:</td>
<td>Proportional Integral (controller)</td>
</tr>
<tr>
<td>ZEBRA:</td>
<td>Zero Emission Battery Research Activity (TM)</td>
</tr>
<tr>
<td>VRB:</td>
<td>Vanadium Redox Battery (TM)</td>
</tr>
<tr>
<td>PCS:</td>
<td>Power Conversion System</td>
</tr>
<tr>
<td>BMS:</td>
<td>Battery Management System</td>
</tr>
<tr>
<td>SOC:</td>
<td>State-of-Charge</td>
</tr>
<tr>
<td>DOD:</td>
<td>Depth-of-Discharge</td>
</tr>
<tr>
<td>OCV:</td>
<td>Open Circuit Voltage</td>
</tr>
<tr>
<td>Aux:</td>
<td>Auxiliary (systems)</td>
</tr>
<tr>
<td>PCC:</td>
<td>Point of Common Coupling</td>
</tr>
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1 INTRODUCTION

1.1 Power systems evolution

Long-term energy security depends on the continuing availability of fossil fuels and their potential substitution by renewable energy sources. Coal and gas may well dominate the global primary energy supply for the rest of this century if no special effort is made to promote renewable sources. However, for many countries energy security concerns are accompanied by a preference for renewable options, which can reduce the dependence on imported oil and gas, as well as helping to meet environmental policy objectives. Hopefully there is a clear focus in the European Union on promoting low-carbon generation technologies and renewable sources, with new and binding targets of 20% of power generation from renewable sources by 2020 [1], [2].

In order to manage this new amount of renewable and generally uncontrollable generation, the electric distribution power systems are thus evolving from passive to active systems, where the word active is referred to the fact that loads and both conventional and renewable generators can play a significant role into the electricity market.

The traditional concept of system with energy generated by few localized and large power plants is changing in a concept where a meshed system with distributed medium and small scale generators. Some typologies of these generators embedded into the network are fed by renewable sources like wind and sunlight. The main drawbacks are their hardly predictable behaviour and uncontrollable output. This means having for example maximum production during minimum demand period or excess of generation in congested parts of the electric network, thus causing bottlenecks and overvoltage situations in some critical sections of the grid [3], [4]. However the presence of storage systems could grant a relief in congested areas of the electric system and permit to operate and dispatch renewable sources with overall optimised goals.

All these challenges can be solved only by study and research activities. Proper simulated models has to be realized, analyzed and tested on the field. Thus the aim of this thesis is to study the main dynamics that characterizes a full converter wind turbine and two different electrochemical storage technologies and to develop dynamic models. These models, realized in Matlab-Simulink simulation environment, are intended to provide a characterization of the stand alone systems and will be validated on real devices. A possible coupling of the two models, that means a wind farm composed by five turbines coupled with one large storage device, is also envisaged and system control strategies are analyzed.
1.2 Wind power in power systems

1.2.1 The wind turbines

Wind power is one of the most promising renewable sources, but it is also the more challenging to manage. To better comprehend the impact that wind power can have on power systems is necessary to understand how a wind turbine produce energy and how the wind, its prime mover, behaves. The wind turbine converts some of the available energy in the moving air mass, into rotational kinetic energy, which is turned into electrical energy by a generator. In order to produce electric energy, there has to be sufficient wind speed for the wind generator to operate. This speed value is referred to as the cut-in wind speed, see Figure 1-1.

As the wind speed increases, the power production also increases and eventually reaches the nominal power at the rated wind speed. As the wind speed continues to increase further, the power production has to be limited, in order not to exceed the maximum mechanical stresses for which the wind generator has been designed. At the cut-out wind speed the wind turbine is stopped, as the mechanical stresses would otherwise be potentially destructive.

The cubic dependence of produced power from wind speed implies that even a slight wind variation can bring large power output swings. That is particularly true when the wind is blowing in the range generally included between 7 and 11 m/s, due to the pronounced steepness of the power curve. It can happen that the power goes from full power to 20% power and back again within few minutes’ periods and large swings can also be seen at other times. When a large number of wind generators are connected together to form a wind farm there is some averaging of the output power in the short term. This kind of compensation is quite natural because, when a wind gust impacts on the wind turbines belonging to the same farm, it does it with a certain delay and, probably, also with different magnitude. The more the parks are clustered, that means the bigger is the area considered, the smoother is the wind
power injected in the network. Figure 1-2 shows an example of wind power production in two macro-areas (Spain and Ireland) on 11/01/2011.

Figure 1-2. Wind power production in Spain (left) and in Ireland (right) on 11/01/2011.

Depending on the day of the year and on the weather situation (i.e. if a low-pressure system is passing through the region, how fast is its movement and how deep is its low centre) and in function of the size and of the orography of the region the wind output can be quite constant as in case of Spain or quite variable as in the case of Ireland or it can be the contrary as depicted in Figure 1-3 on 26/12/2010 [5], [6].

Wind should be thus considered as an energy source, rather than a power source since its availability will depend on the weather and cannot be considered to be available all the time. Averaged over a year the produced electric energy can be estimated with reasonable accuracy, but even from one year to another the energy production may vary.
1.2.2 Power system operation

The function of an electric power system is to convert energy from one of the naturally available forms to the electrical form and to transport it to the points of consumption. Here the energy is generally converted into other forms depending on the purpose (mechanical, thermal, etc...). The main advantage in the use of the electrical energy is that it can be easily transported and controlled with a high degree of efficiency and reliability [7]. A properly designed and operated power system should, therefore, meet the following requirements:

- The system must be able to follow the continually changing (but fortunately predictable) load demand. Unlike other types of energy, electricity can be hardly stored in sufficient quantities.
- The system should supply with minimum ecological impact and at minimum cost.
- The quality of power supply must meet certain standards, identified by a constancy of frequency and voltage and a high level of reliability.

The main actors of the power systems are the power stations. Conventional power stations typically use synchronous generators with a highly predictable supply of “fuel”, be this hydro (when based on substantial water reservoir otherwise it can be also intermittent), nuclear, coal, oil, gas or other resources. In addition to providing electrical energy to the network they also provide a number of other services, as described below. The operation of a network with conventional generation has been described in several books and publications so here only a brief overview will be provided [8].

Scheduled Power Generation: Large conventional power stations can be scheduled for a certain constant power level, provided that there is input energy available. The schedule for individual generators may be decided by the system operator to suit the load demand and to take into accounts overall economics and system security constraints. In unbundled electricity markets, the generators are scheduled as a consequence of the day-ahead market decisions, within boundary conditions set by the TSO, and with the system operator arranging for balancing power to compensate for any power shortages or excesses.

F/P Control (Frequency Power Control): In order to ensure that the network is secure in the event of a trip of a major power station or transmission resource, the total generation resource connected will be increased to provide a margin above the forecast maximum demand (spinning reserve). Some of the generators will not be operating at their maximum possible output during normal conditions. Typically, three levels of control ensure that constant system frequency is maintained and the power balance is restored:
• The primary control is an automatic function of each generator governor in the network to quickly adjust the output of the unit in reaction to the frequency change, in order to restore the balance between supply and loads. The balance is restored, but the frequency may deviate from its original value.
• The secondary control is a centralized automatic generation control (AGC) function to regulate the output of one or more generators such that the frequency returns to its nominal value.
• The tertiary control loop, generally manually operated in the TSO control room provides to reschedule the power stations in order to restore the operating margins in the power system.

**Inertial Response:** Inertia refers to the stored rotational energy in the generator and it reflects the degree to which rotating masses oppose changes to the power frequency. The rate of change of frequency after a mismatch in the demand and supply balance is related to the system inertia. The generators, including their prime movers, typically have a large rotating mass, which provides a steadying influence on the generator voltage phase angle. This increases the time constant of swings and disturbances in the ac network and it stabilizes the frequency response to changes in the demand/supply balance.

**V/Q Control (Voltage Reactive Power Control):** The excitation control enables the generator to control the ac voltage at its terminals through the absorption or generation of reactive power. Typically, this vital role for the network is performed through an Automatic Voltage Regulator (AVR) which will have a steady-state control target as well as a sloping characteristic.

**PSS (Power System Stabilization):** Some of the generators may be fitted with power controllers (power system stabilizers, which act through the excitation system) designed to damp power swings in the network. This can be particularly useful when the network has distinct areas with large concentration of loads and generation interconnected by long weak lines.

**Fault Current Contribution:** During a fault in the ac network the generators continue to provide current into the ac network. The fault current that may be experienced by switchgear and other equipment in the network is often one of the key dimensioning design factors, and in some cases it is necessary to introduce measures aimed at reducing the fault current. On the other hand most types of conventional fault protection used in an ac network depend on the presence of high amplitude current during fault conditions for its correct operation.
Fault Ride Through: In the event of a fault in the ac network, the generators may experience large overcurrents and power swings both during the fault and after its clearance by the appropriate switchgear. The conventional generators are designed with these stresses in mind and continue to be connected to the network during and after the fault, such that the power supply system can return to normal conditions immediately after the disturbance. Generators very close to a fault are allowed to trip if the critical fault clearance time of that unit is not met, but tripping is then limited only to typically one unit/power plant only, so that the power supply system, as a whole, is not jeopardized.

Wind generation can in principle be used for the provision of most the previously described services, depending on the wind available at a specific time. Naturally, as is also the case for conventional generation used for this purpose, the wind generators would then not be operated at their maximum power production capability, but instead at a reduced value. It should be pointed out that an important difference is that, in the case of curtailing wind energy, this ‘green’ form of energy gets lost, whereas in hydro and fossil power plants the energy source is saved and can be used later. The “fuel” costs of the power plant do not decrease during curtailment, which causes some reluctance by wind farm operators towards curtailment as virtually all production costs consist of capital costs.

1.3 Need for storage

1.3.1 Storage for the power system

As foretold, the main challenge with a large penetration of wind generation in a network is to manage the uncertainty of the amount of generation that will be available at any specific time, particularly if high wind is expected. The presence of energy storage systems could allow a better management of the electric system allowing the full exploitation of renewable energy sources. Nowadays the cost per stored energy is quite high and so it might not be economically feasible to install huge amount of batteries. The size of the storage systems can considerably vary and, depending on their sizes, different tasks can be performed as shown in Figure 1-4 [9], [10], [11], [12]. Hence the possible duties range from short-term fluctuation levelling and power quality improvement to primary frequency-power regulation and, in case of large storage sizing, compliance to day-ahead generation dispatching. Energy storage has been the most challenging and complex issue of the industry whether for the electric utilities or for industrial applications. The constant need for efficient energy storage has seen the emerging of new technologies which promise reliability, productivity and the use of renewable.
Available energy storage systems range from short term (seconds to minutes) to long term (hours and days) storage, as shown in Figure 1-5 [13].

Figure 1-4. Storage power requirements for electric power utility applications.

Figure 1-5. Storage system ratings.
Energy storage, using pumped storage, has been used for decades and large systems can be found in many countries. A large number of different types of battery technologies with different characteristics are available today. Installations using flow type batteries with large tanks for the electrolyte to create long term storage have been developed, but large scale application of these systems has not yet taken place. This storage technology has been successfully implemented in Utah (US) (250 kW -1000 kWh), on small scale to manage peak flows in distribution feeder [14]. The overall efficiency of the charge/discharge cycle is about 65%. The technology offers fast response and good short term overload capability (50 to 100% for 60 seconds) and quick recovery to support the next overload cycle (also 60 seconds) making it suitable to manage wind intermittency. Another project is intended to manage the 51 MW Fututama (Japan) wind farm with a massive installation of 34 MW - 204 MWh NaS batteries system.

1.3.2 Possible tasks for storage

In principle, the DC/AC inverter required to interface a battery storage system with a network, is based on the same concept as a static compensator (STATCOM) with the only difference that a battery is used in the DC side instead of a capacitor. Storage can thus be used to complement primary generation as it can be used to store energy during off peak periods and release it later during peak demand. Storage can play a multi-function role, further on detailed, in the electric supply network to manage the resources effectively [15].

Transmission Curtailment: the mitigation of constraints imposed by insufficient transmission capacity on the utilization of wind generation requires that energy be stored during periods of insufficient transmission capacity and discharged when capacity becomes available.

Generation Shifting: wind generation time-shifting means to store the energy generated during daily periods of low demand (off-peak, 6:00 pm to 6:00 am) and to discharge it during periods of high demand (on-peak, 6:00 am to 6:00 pm).

Forecast Error Compensation: wind generation forecast hedging applications would use stored energy to mitigate penalties incurred when real-time generation falls short of the amount of generation bid for delivery. Short term variability in wind farm output results in an economic risk that real-time generation will be more or less than the bid amount, and these risks are managed by using a combination of wind generation forecasting techniques and bidding strategies to minimize penalties due to shortfalls.

Grid Frequency Support: it provides short duration power necessary to maintain grid frequency steady within a nominal range following a severe system disturbance caused by a
significant imbalance between generation and load. In systems with a high fraction of generation provided by wind generation, a sudden reduction in wind can cause such a disturbance.

**Fluctuation Suppression:** Wind fluctuation suppression applications would use stored energy to stabilize wind farm generation frequency by absorbing and discharging energy counter to high cycle variations in output.

### 1.4 The simulation environment: Matlab-Simulink

The models of the wind turbine and of the storage system, whose description begins in the next chapter, have been developed in Matlab-Simulink. A very short description of the main functionality of this simulation environment is here reported [16].

Simulink provides a graphical interface in order to build the models so as block diagrams, or to modify existing models. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. It also includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors and in case of need one can also create his own blocks. The interactive graphical environment simplifies the modeling process, eliminating the need to formulate differential and difference equations in a language or program. Model-Based Design is a process that enables faster, more cost-effective development of dynamic systems, including control systems, signal processing, and communications systems. In Model-Based Design, a system model is at the centre of the development process, from requirements development, through design, implementation, and testing. The model is an executable specification that is continually refined throughout the development process. After model development, simulation shows whether the model works correctly.

After a model has been defined, dynamic simulations can be run, using a choice of mathematical integration methods, either from the Simulink menus or by entering commands in the Matlab command window. The menus are convenient for interactive work, while the command line is useful for running a batch of simulations (for example, in Monte Carlo simulations). The integration of Simulink with the Matlab environment can also be very advantageous for data simulation post processing.

When software and hardware implementation requirements are included, such as fixed-point and timing behaviour, the developed code can be generated for embedded deployment and to create test benches for system verification.
2 WIND TURBINE MODEL

2.1 Turbine Technologies

2.1.1 General remarks

In the 1990s the wind turbines were generally designed to operate at constant speed. It means that, regardless of the wind speed, the turbine’s rotor speed is fixed and bound to the frequency of the main network. The generator generally adopted was an induction machine, which presents several advantages, such as robustness, mechanical simplicity and low cost due to large series production. On the contrary it requires reactive power from the stator to be magnetized and thus the more active power is produced the more reactive power is drawn. Moreover, due to the intrinsically steep torque-speed characteristic, all the fluctuations in wind power are transmitted in the network.

Recently the variable speed concept has become the dominant type among the installed wind turbines. Variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds, by changing the shaft rotational speed. The electro-mechanical conversion system is more complicated compared to the previous one. It is typically equipped with an induction or a synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed; thus there is the possibility to compensate much more easily the wind fluctuation.

The main advantages of variable-speed wind turbine are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages reside in the increased degree of complication of the system and thus the increased capital cost.

As foretold, once the wind blows stronger than the nominal speed, the power production has to be limited. The limitation of the output power in the wind speed area between rated and cut-out is achieved by reducing the efficiency of the aerodynamic conversion of wind energy into rotational kinetic energy. This can be done by utilizing the turbine blade profile in two different ways. The blades can be designed in such a way that they lose their efficiency as the wind increases; this method is called stall regulation. Alternatively, the blades can be turned out of the wind; this method is called pitch regulation. Stall regulation was mainly used for the earlier wind generators, and is also used today for fixed-speed wind generators, while pitch control is used for variable speed generators [17].
2.1.2 Wind turbine family

It is common practice to group the wind turbines produced worldwide in four main typologies depending on the type of generator they are equipped with (see Figure 2-1):

A) Fixed speed induction generators.
B) Small variable speed induction generators.
C) Variable speed doubly fed induction generators.
D) Variable speed full converter with synchronous or asynchronous generators.

![Figure 2-1. Wind Turbines Typologies.](image)
The first concept, the type A, is the oldest and the cheapest wind turbine: it consists of a directly grid-connected squirrel-cage induction machine (SCIM), the rotor of which is connected to the turbine shaft through a gearbox. Because of its nature the induction machine consumes reactive power from the grid whether it is operating as a motor or as a generator. Hence a capacitor banks is usually connected at SCIM terminals for reactive power compensation. This turbine type is often referred to as a fixed speed because its rotational speed range is very small due to the nature of the asynchronous generator. The fluctuations in the wind power are converted in mechanical and then electrical fluctuations and in the case of weak grids this can cause significant voltage variations. Moreover the changes in the voltages cause variation in reactive consumption, which leads to further voltage drops and thus causing the risk of voltage instability. This is the cheapest WTG technology, and before the advent of stringent grid code requirements it was the most popular WTG concept.

WTG type B is very similar to type A, except that now there is a variable rotor resistance in the induction machine. This variable rotor resistance can be achieved using a wound rotor induction machine (WRIM), which gives electrical access to the rotor circuits. The unique feature of this concept is that it has a variable additional rotor resistance, which can be changed by an optically controlled converter mounted on the rotor shaft, granting thus the controllability of the total rotor resistance. Typically the speed range was 0÷10% above synchronous speed. The best known manufacturer of this technology is Vestas.

WTG type C also uses an induction machine. This time the induction machine is always a WRIM. The stator circuit is connected directly to the grid and the rotor circuit is connected to the grid using a pair of back-to-back pulse width modulated voltage source converters (PWM VSCs). The partial scale converter performs the reactive power compensation and grants a smoother grid connection by the partial compensation of the wind turbulence. It has a wider range of dynamic speed control compared to the previous one and, depending on the converter size, generally ranges from -40% to +30% referred to the synchronous speed. The main drawbacks are the use of slip rings and the need of protecting the converter during grid faults against rotor overcurrents and DC-link overvoltages. This is most commonly known as a doubly-fed induction generator (DFIG), and it is by far the dominant WTG technology in the market. There are a number of manufacturers who supply DFIG, and their protection systems may have some differences.

WTG type D includes all the turbines whose generator (either synchronous or asynchronous) is fully decoupled from the grid, by means of an electronic converter. Hence this converter must be rated at the nominal power of the WT, making it the most expensive concept to manufacture. Depending on the manufacturer, different solution has been realized by using
excited (Enercon) or permanent magnet (General Electric) synchronous generator directed coupled to the turbine shaft, as well asynchronous machine (Siemens) connected through a (smaller) gearbox to the shaft. The connection through the full converter grants complete freedom in the choice of the electromechanical system, hence other solutions could be realized in the future. In any case the grid response is always characterized by the behaviour of the PWM converter [18], [19].

2.1.3 Wind turbine costs

In 25 years wind energy technology has developed enormously. The rotor diameter passed from few meters in 80s for the first commercial turbines to 52-80 meters for the mostly common installed machine with 850 kW and 2000 kW generators and it is now getting to about 150-180 m for the titanic offshore turbines. With more R&D investment, turbines can continue to become even more efficient and high performing.

Figure 2-2. Size evolution of wind turbines over time.

Figure 2-3, taken from [20], shows the progress in the turbines installation rate across the World. By the end of 2010 near 200 GW of wind turbines were installed and the capacity has been doubling every three years.
In Europe, with an expected value of 84 GW installed by the end of 2010 and an energy production around 180 TWh, wind power is estimated to cover above 5% of the 3400 TWh consumed. Figure 2-4 reports the wind share in the electricity consumption of the European Nations [21]. Several Countries such as Denmark, Spain, Portugal, Ireland and Germany are already covering a consistent amount of their needs thanks to the wind.

The EWEA forecasts a coverage around 14% of the Europe’s total electricity demand in 2020 (494 TWh from 213 GW installed capacity).
The installation costs have progressively been reduced due to the technology improvements and to the development of bigger machines. A first evaluation figures the capital cost per kW between 1000 and 1500 €/kW for inland installation and about 2000-2500 €/kW for the offshore one. The local terrain complexity, as well as the distance from the shore, and the distance from the main network, are important variables in determining the final cost.

A deep analysis is done in [22] and the most significant graphs are here reported. Figure 2-5 shows the cost projection of the European Commission in the 2000 and the one estimated by the EWEA, considered the recent aerogenerators peak demand. It is worth noting that the peak cost in the 2007-2008 was caused by the massive increase in wind farm project, hardly matched by the manufacturer production. In a similar way in this moment there is a huge interest in offshore wind farms, for which about 40 GW just in the North Sea are expected at 2020, but the current absence of economies of scale due to low market deployment and bottlenecks in the supply chain are still reflecting in the final installation cost. Moreover many manufacturers are still testing the offshore products, whose reliability and resistance to the sea agents are a must.

![Figure 2-5. Onshore and Offshore capital costs.](source=EWEA, 2007)

In the next year, though, the prices should stabilize just below 1000 €/kW for the onshore and 1500 €/kW for the offshore. Next graphs show the energy cost in function of the wind speed area (expressed as the equivalent number of full power hours per year), considering different values of capital cost and assuming a 7.5% discount rate (see Figure 2-6).
Figure 2-6. Wind energy cost in function of the wind speed and of the capital cost, assumed a discount rate of 7.5%.

Wind energy cost value is becoming very similar to the conventional power plant energy cost. Figure 2-7 reports a sensitivity analysis in function of the discount rate.

Figure 2-7. Wind energy cost in function of the wind speed and of the discount rate, assumed a capital cost €1200/kW.

The wind turbines are, in fact, a capital intensive investment: the capital cost weighs for about the 75% of the final energy cost, as the remaining is due to the operation and management. Thus the variations of the discount rate are reflected in the final energy cost. Also the small size wind power (< 20 kW), even if in absolute terms its diffusion has less impact, is now facing a market growth with new models and new concepts for both horizontal and vertical axis turbines. The costs are about 2000-3000 €/kW.
2.2 Wind turbine model description

2.2.1 Main assumptions

The wind turbine model realized is described from an electromechanical perspective, thus it provides: an analysis of the aerodynamic behaviour of the rotor including the pitch control system, the shaft dynamic and the maximum power tracking characteristic [23]. The model is tuned for a 2 MW full converter direct drive equipped generator. This typology of wind turbine is characterized by the absence of the gearbox and the presence of ac/dc/ac converter sized for the whole power. Since the model is not intended to analyze dynamics faster than a fraction of second, there is no need to characterize in a detailed way the generation/conversion system, which thus it is modeled as a negative load [24]. The rest of the electromechanical conversion system needs an accurate detail due to the interest in studying the possibility to reduce the output in certain conditions. There is, in fact, the need to model the delays introduced by the pitch controller and by the shaft rotational speed [25].

The block diagram that describes the main model components and their mutual interaction is depicted in Figure 2-8. Reading the picture from left to right the first block met is the Aerodynamic one that evaluates the power harvested by the rotor that depends on wind speed, rotational speed and blade angle. This accelerating power, along with the rotational speed of the generator, enters the block named Shaft that describes the shaft behaviour and allows the evaluation of the power at the end of the shaft and of the turbine rotational speed. The blade angle is controlled by the Pitch Control that describes the dynamic of the pitch actuators.

The accelerating power at the end of the shaft is the input for the block called Generator and MPT (Maximum Power Tracking) that describes the dynamic of the generator, the MPT control characteristic, and the efficiency of the conversion system. At the end the electrical power produced is calculated and it is the main output of the turbine model.
The rest of the paragraph develops as follow:

- Wind speed data
- Rotor aerodynamic
- Shaft dynamic
- Maximum Power Tracking
- Pitch controller

### 2.2.2 Wind speed data

When studying the wind turbine output, special care should be devoted to the analysis and the proper use of the wind speed data. For power systems studies it is common practice to consider just one wind profile per turbine while, in reality, during their sweeping action the blades face different wind profiles: this variety is generated by the turbulence induced by the local terrain. This assumption however is commonly accepted as long as this wind is representative of the wind seen by the whole rotor and it is generally called hub wind [26].

Due to the interest in studying the fluctuation induced in the turbine power output it is necessary to have appropriated wind speed data or an accurate wind model. For this purpose, data related to the power outputs and to the wind speeds measured at the nacelle of five wind turbines belonging to the same farm are used [27]. The data are sampled with a five seconds time step that gives accurate information on the fluctuation included in the wind. A comparison between the wind speeds, measured by the anemometer placed in the rear of the nacelle, and the electrical output power highlights that the wind measured by the anemometer is not necessary the same that is seen by the whole rotor. As depicted in Figure 2-9, it can be seen that there is a tight correlation between the winds measured data and power output. This correlation determines the datasheet power curve of the turbine, although being this correspondence not exact.

Due to this weak correlation, it is chosen to evaluate the wind speed starting from the output power profile by means of the static power curve of the turbine. Moreover the reduction in the power output due to the height of the installation of the farm, caused by the lower atmospheric pressure compared to sea level, is taken in account. The wind series thus created contain information related to the turbulence due to the local terrain roughness or others as for example the tower shadow effect or the wake of the surrounding machines.

Figure 2-10 offers a visual comparison between two 24-hours series of wind speeds: the one on the left side reports the wind measured at the nacelle, while the one on the right side shows the wind calculated from the power production, calculated by means of the proper power curve. As it can be noticed the wind profile calculated is smoother because the wind measured by the nacelle anemometer has the turbulence induced by the blades themselves.
To analytically evaluate the turbulence it is common practice to introduce the turbulence intensity, generally defined as the ratio between the standard deviation, $\sigma$ (m/s), and the average wind speed, $U$ (m/s), in a 10-minutes length wind series:

$$
turbulence\ \text{intensity} = \frac{\sigma}{U}
$$
\[ I = \frac{\sigma}{\bar{U}} \] (2-1)

In the specific case the overall average wind speed, on all the 24-hours profile, values respectively 7.59 and 7.52 m/s, while the average turbulence intensity, calculated as the average of all the 10-minutes measures, values 11.5% for the wind series measured at the nacelle and 8.3% for the one evaluated from the power output. Figure 2-11 shows the two 10-minutes average wind speeds and the related turbulence intensity profiles.

![Average Wind Speed](image1)

![Turbulence Intensity](image2)

Figure 2-11. Measured and Evaluated winds: 10-minutes average (first diagram) and turbulence intensity (second diagram).

However, considering that these data come from a 850 kW machine, whose hub height is about 60 meters above the ground level, the wind speed at 90 m height has been evaluated considering the local terrain roughness. In fact, the more the terrain is rough, the more the wind slows down when the quota decreases. It is assumed that the 2 MW wind turbines in this study have the hub at about 90 meters. Thus the wind quota report is done by introducing the wind shear coefficient \( \alpha \) values:

\[ \alpha = \frac{1}{\ln\left(\frac{h}{z_0}\right)} \] (2-2)

---

**Mattia Marinelli: Wind Turbine and Electrochemical Based Storage Modeling and Integrated Control Strategies to Improve Renewable Energy Integration in the Grid**
Where \( h_1 \) (m) is the reference wind quota and \( z_0 \) (m) is the roughness length in the current wind direction (in this case 0.1 m, appropriate at describing an agricultural land with few obstacles) [28], [29]. Hence the required wind speed, \( U_2 \) (m/s) at the new height \( (h_2) \) is calculated as follows:

\[
U_2 = U_1 \left( \frac{h_2}{h_1} \right)^{\alpha} \tag{2-3}
\]

The obtained wind profiles are reported in Figure 2-12 (24h length) and Figure 2-13 (detail).

![Figure 2-12. Windspeeds at 60 and 90 meters above the ground.](image)

![Figure 2-13. Windspeeds (detail).](image)
In addition, the five turbines, are fed by different wind speeds profiles calculated, shown in Figure 2-14, as explained previously, from the power output of the five wind turbines belonging to the same farm.

![The Five WindSpeed](image)

**Figure 2-14. Five wind speed profiles, 5-seconds sample time, 24-hours timeframe.**

The characteristic values of the above shown wind profiles, such as max-mean-min speed and the average turbulence (evaluated in 10-minutes length window) are reported in Table 2-1. Wind speed profiles summary.

<table>
<thead>
<tr>
<th></th>
<th>Wind 1 @ 90m</th>
<th>Wind 2 @ 90m</th>
<th>Wind 3 @ 90m</th>
<th>Wind 4 @ 90m</th>
<th>Wind 5 @ 90m</th>
</tr>
</thead>
<tbody>
<tr>
<td>U max</td>
<td>16.9</td>
<td>16.8</td>
<td>16.7</td>
<td>16.8</td>
<td>12.5</td>
</tr>
<tr>
<td>U mean</td>
<td>8.0</td>
<td>7.8</td>
<td>7.6</td>
<td>7.4</td>
<td>6.8</td>
</tr>
<tr>
<td>U min</td>
<td>3.3</td>
<td>3.1</td>
<td>3.1</td>
<td>2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Mean 10-min turbulence</td>
<td>8.3%</td>
<td>8.6%</td>
<td>8.8%</td>
<td>8.8%</td>
<td>9.9%</td>
</tr>
</tbody>
</table>

**Table 2-1. Wind speed profiles summary.**
2.2.3 Rotor aerodynamic

The power that the rotor of area, \( A \, (\text{m}^2) \), can extract from the wind flux depends mainly on the wind speed, \( U \, (\text{m/s}) \), the air density, \( \rho \, (\text{kg/m}^3) \), and rotor aerodynamic efficiency, \( c_p \, (\text{pu}) \), which is also known as power coefficient and quantifies the amount of power that the rotor extracts from the wind, \( P_{\text{rotor}} \, (\text{W}) \) [30]:

\[
P_{\text{rotor}} = \frac{1}{2} c_p \cdot \rho \cdot A \cdot U^3
\]  

(2-4)

This coefficient is function of the tip speed ratio, \( \lambda \, (\text{pu}) \), and of the blade pitch angle, \( \beta \, (\text{deg}) \). The value of \( \lambda \) depends on the ratio between blade peripheral speed and wind speed:

\[
\lambda = \frac{\omega \cdot R}{U}
\]  

(2-5)

A possible analytic representation can be expressed by the following equation:

\[
c_p = c_1 * \left[ c_6 * \lambda + \frac{-c_4 - c_5 * (2.5 + \beta) + c_2 * \frac{1}{\lambda + c_7 * (2.5 + \beta) - \frac{c_3}{\lambda + (2.5 + \beta)^3}}}{\exp[c_3 * \frac{1}{\lambda + c_7 * (2.5 + \beta) - \frac{c_3}{\lambda + (2.5 + \beta)^3}}]} \right] + c_9 * \lambda
\]  

(2-6)

Where the coefficients \( c_i \) are:

<table>
<thead>
<tr>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( c_4 )</th>
<th>( c_5 )</th>
<th>( c_6 )</th>
<th>( c_7 )</th>
<th>( c_8 )</th>
<th>( c_9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.645</td>
<td>116</td>
<td>0.4</td>
<td>5</td>
<td>21</td>
<td>0.00912</td>
<td>0.08</td>
<td>0.035</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 2-2. Coefficient values.

The graphical representation of the power coefficient curves in function of the tip speed ratio and parameterized at different pitch angle values is depicted in Figure 2-15.
2.2.4 Shaft dynamic

Wind turbines have a relatively soft shaft, and the eigenvalues of the drive train are inside the range of values normally taken in account for power system studies (0.1 ÷ 10 Hz). Moreover, the greater is the number of pole pairs of the generator the softer gets the shaft [31]. This can cause the initiation of oscillations whenever there is a sudden step of torque, due for example to wind gust or faults on the network.

In fact, whenever there is a sudden difference between mechanical and electrical torques, respectively $T_{\text{wind}}$ and $T_{\text{electromagnetic}}$ (Nm), the two shafts, the one of the turbine and the one of the generator, have the possibility to rotate one against the other, thus there is the need to define two different rotational speeds: $\omega_{\text{turbine}}$ and $\omega_{\text{generator}}$ (rad/s). A two masses representation is therefore necessary due to the interest in evaluating the oscillations induced by the wind in the power output. The differential equations that describe the dynamic of the system are reported below: starting from the response determined by the inertia of the turbine, $J_{\text{turbine}}$ (kg m$^2$), passing through the shaft stiffness, $k$ (Nm/rad), and damping, $D$ (Ns/rad), values getting to the generator inertia, $J_{\text{generator}}$:

$$
\begin{align*}
T_{\text{wind}} - T_{\text{shaft}} &= J_{\text{turbine}} \frac{d\omega_{\text{turbine}}}{dt}, \\
\omega_{\text{turbine}0} &= \omega_{\text{initial}}
\end{align*}
$$

Figure 2-15. Power Coefficient characteristic plotted in function of the Tip Speed Ratio (lambda) and parameterized with the pitch angle (beta).
\begin{equation}
T_{\text{shaft}} = k \dot{\vartheta} + D (\omega_{\text{turbine}} - \omega_{\text{generator}});
\end{equation}
\begin{equation}
\dot{\vartheta} = \int (\omega_{\text{turbine}} - \omega_{\text{generator}}) \, dt;
\end{equation}
\begin{equation}
\vartheta_0 = \frac{T_{\text{shaft0}}}{k}.
\end{equation}
\begin{equation}
T_{\text{shaft}} - T_{\text{electromagnetic}} = J_{\text{gen}} \frac{d \omega_{\text{generator}}}{dt};
\end{equation}
\begin{equation}
\omega_{\text{generator0}} = \omega_{\text{initial}}.
\end{equation}

In order to help the comprehension of the shaft dynamics, a comparison with an electrical equivalent system can be done. In fact, if it is assumed that the torques behave like the currents and the rotational speeds like the voltages then the inertial effects are described by means of capacitors, the stiffness by means of inductors and the damping by means of resistances. The electrical circuit is shown in Figure 2-16.

Figure 2-16. Electrical equivalent of the two masses shaft.

It is sometimes useful to introduce the per unit system, widely used in the electrical world, also for the mechanical variables. This allows for example to easily compare the inertia and the stiffness values for different rated power machines.

For the modeled turbine the following values, reported in Table 2-3, are used:

<table>
<thead>
<tr>
<th>Nominal Power</th>
<th>Nominal rotational speed</th>
<th>Turbine Inertia</th>
<th>Torsional Stiffness</th>
<th>Torsional damping</th>
<th>Generator Inertia</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 MW</td>
<td>19.5 rpm (2.04 rad/s)</td>
<td>6e6 kgm²</td>
<td>10e6 Nm/rad</td>
<td>5e5 Nms/rad</td>
<td>5e5 kgm²</td>
</tr>
</tbody>
</table>

Table 2-3. Shaft parameters.
2.2.5 Maximum Power Tracking

As already described in the aerodynamic characteristic, the maximum efficiency is available only for a small range of values of λ. Thus, since the wind is continuously changing, the Maximum Power Tracking (MPT) has to control the generator rotational speed, ω, in order to have the desired (and optimal) power output. This tracking action is realized by following the blue curve, shown in Figure 2-17, which generates the reference power in function of the rotational speed of the turbine.

In theory it would be better to express the reference power as function of the wind speed, which, unfortunately, cannot be measured with accuracy. So, instead of using wind speed, another control variable, the rotational speed of the turbine is used [22], [25].

The logic behind this curve is quite simple: the control system sets a reference value of power to the generator, depending on the actual rotational speed, and, if the torque that the generator imposes on the shaft is greater than the one caught by the rotor blades, then the shaft slows down. Hence the reference power is reduced and if it is equal to the one produced by the turbine the system is steady otherwise the tracking action goes on.

![Maximum Power Tracking Curve](image)

Figure 2-17. Power reference (MPT characteristic) and $c_p$ in function of the rotational speed.

This curve can be divided into three zones:

- The first one goes from the cut-in rotational speed (40% of the nominal speed) to the 90% of the rotational speed and describes the part where the turbine is pursuing the
maximum power coefficient (depicted by the red curve) and covers the wind range between 3 to 9 m/s.

- The second zone is characterized by the steep increase in the reference power and it is due to the fact that there is no more interest in collecting all the power in the wind because it is blowing close to the nominal values. Thus the power coefficient, $c_p$, is progressively reduced. It includes the winds between 9 m/s and the nominal one, which is equal to 12.5 m/s for the modeled turbine.

- The last one is characterized by a flat curve that sets the nominal reference power to the generators and allows the machine to go in overspeed to absorb the rapid wind speed variations. Generally a 20% of overspeed is acceptable and a slight increase of the power output (about 4%) can help to reduce the stress on the pitch blade actuators. The wind speed covered by this area obviously ranges from the nominal wind speed to the cut-out one (25 m/s). The $c_p$ curve is no more represented since from there the blade angle can assume different transient values from 0° (optimal angle) to 32° and hence it is not possible to define a unique power coefficient value.

Figure 2-18 reports the influence of the reference power set by the MPT curve in the modeling block diagram. It has been assumed a certain delay (0.1 seconds) between the evaluation of the reference power and its setting to the power converter. As it can be seen this reference power value can be modified by an external control signal that reduces the reference power in order to force a reduction in the turbine power output in case of request by the overall park controller. This reduction in the electromagnetic torque (the braking one) will cause an acceleration of the turbine speed that will be duty of the pitch control system to counteract.

This signal can also be sensible to the frequency value and thus, for example, it commands a reduction of the optimal power if the frequency rises above a certain threshold (i.e. 50.5 Hz) or can enhance an emulation of the inertial response of the machine. This can be done by means
of a specific transfer function which forces to release a certain amount of kinetic energy to counteract the frequency rate of change [32], [33], [34]. The electromechanical power signal is then reduced by the generator efficiency (assumed constant and equal to 98%). At last the PCS losses (assumed constant and equal to 95%) and the auxiliary consumption (10 kW, i.e. 0.5% of the nominal rating) are deduced from the power produced by the generator and the power available at the connection point is computed.

2.2.6 Pitch angle control

The pitch control system has to reduce the aerodynamic efficiency by increasing the blade attack angle. Its control is sensible to rotational speed: if this value goes above 1 per unit, the PI (Proportional Integral) control system commands the increase of the blade pitch angle. The controller values are 40 for the proportional gain, $k_p$, and 0.1 seconds for the integrator time constant, $T_i$. Figure 2-19 shows the block diagram of the pitch control system that includes also the delay of the actuator that is realized by the integrator with unitary feedback (on the right side of the figure). This time constant generally is 0.5 seconds while the rate of change, i.e. the changing speed of the blades, is about $\pm 5$ deg/s with a minimum angle of 0 deg and a practical maximum angle of about 32 deg, for the blade shape adopted in this model.

![Figure 2-19. Block diagram of the pitch controller.](image)

2.3 Wind turbine model testing simulations

2.3.1 Wind steps response

First of all the turbine model is tested by means of a series of wind steps, shown in the first diagram of Figure 2-20 along with the pitch angle curve. Thus the dynamic response of the wind turbine is tested by a sequence of wind steps (60 seconds length) starting from 3 m/s (the cut-in speed) to 23 m/s.
The output power can be seen in the second diagram, while the rotational speed in the latter one. As long as the wind speed increases so does the rotational speed and therefore the output power. Once the wind reaches the nominal value (12 m/s) the power does not go above the nominal power (2 MW) and at each wind step the pitch controller keeps under control the rotational speed (1 pu) by increasing the pitch angle (black line in the first diagram). Figure 2-21 offers an overview of the aero dynamical behaviour of the machine. The first diagram shows the increase of wind power with the increase of wind speed and the portion produced by the machine. Because all the components of the machine are rated for 2 MW it is clear that all the amount of power present in strong winds cannot be harvested. The second diagram shows TSR (or lambda), i.e. the ratio between the peripheral speed of the blades and the wind speed, and the pitch angle. As explained previously it is role of the MPT control to tune the rotational speed in order to pursue the optimal TSR (equal to 10 for the aerodynamic characteristic implemented in this turbine model) for light winds. As the wind starts blowing stronger and the rotational speed reaches the limit (1 pu), the TSR is reduced contributing to the reduction of the power coefficient (cp, shown in the third diagram). The reduction of the TSR alone (Figure 2-15), however, is not enough to reduce the cp and, hence, it is necessary also to pitch the blades in order to reduce the lift of the blades.

Figure 2-22 reports the shaft mechanical variables: torques and speeds. At each wind step, that means at each step increase in the kinetic energy available in the wind, the mechanical torque (blue line in the first diagram) suddenly increases.
The turbine speed increases and so does the generator one (with a slight delay not visible in the second diagram). The electrical torque is increased as consequence of the new MPT reference induced by the changing in the generator speed.

Figure 2-22. Mechanical and electrical torques; Turbine and generator speeds.
2.3.2 Turbulent wind response

The next step is to analyze the response of the five wind turbines, each fed by its own wind profile, reported in Figure 2-23.

The first diagram of Figure 2-24 shows the respective power output in per unit on machine base (2 MW). The park output can be seen in the second diagram, in per unit again but on park base (10 MW).
The overall power output certainly benefits from the mutual compensation of the turbines, that is due to the fact that one turbine can see a wind gust that, not necessarily, is seen by the others. The park output profiles, hence, improves with the increase of the machine number, however it is still quite turbulent.

The measure of the power turbulence intensity, defined, similarly to the wind turbulence, as the ratio between the standard deviation and the average power in a 10-minutes basis, is between 19% and 25% (equal to 0.38 MW and 0.5 MW) for the single turbine (see also while it is reduced to 11.8% (equal to 1.18 MW) at the PCC for the 12-hours timeframe considered (see Table 2-4).

<table>
<thead>
<tr>
<th>WT 1 @ 90m</th>
<th>WT 2 @ 90m</th>
<th>WT 3 @ 90m</th>
<th>WT 4 @ 90m</th>
<th>WT 5 @ 90m</th>
<th>FARM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Output Power (pu)</td>
<td>0.606</td>
<td>0.577</td>
<td>0.551</td>
<td>0.528</td>
<td>0.367</td>
</tr>
<tr>
<td>Average Power Turbulence (%)</td>
<td>19.3%</td>
<td>20.1%</td>
<td>20.9%</td>
<td>21.7%</td>
<td>25.7%</td>
</tr>
</tbody>
</table>

Table 2-4. Wind turbines and Farm average power and average power turbulence.

For sake of clarity in Figure 2-25 and in Figure 2-26 the most characteristic variables of the single (the first one) wind turbine are reported. It can be noted how the tracking action, that means the rotational speed control, of the maximum power controller is successfully achieved by taking the TSR always around 10 pu thus leading to a power coefficient equal to 0.5.
The pitch angle is zero during the 3600 simulation seconds here reported because the wind is not blowing strong.

Figure 2-26. Tip Speed Ratio and Pitch; Power coefficient.
3 STORAGE SYSTEM MODEL

3.1 Storage Technologies

3.1.1 High Temperature Batteries: The Sodium family

Since the mid 1960s much development work has been undertaken on batteries using Sodium for the negative electrodes. Sodium is very attractive because of its high reduction potential of - 2.71 Volt, low weight, non toxic nature, relative abundance and ready availability. All these factors offer the prospect of batteries with very high power and energy densities. Unfortunately in order to construct practical batteries using sodium electrodes, the sodium must be used in liquid form. Since the melting point of sodium is 98 °C this means that sodium based batteries must operate at high temperatures, typically above 270 °C. This in turn brings problems of thermal management and safety and places more stringent requirements on the rest of the battery components [35], [36], [37].

The first commercial battery produced was the Sodium Sulphur (NaS) battery which uses liquid sulphur for the positive electrode and a ceramic tube of β-alumina for the electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. Corrosion of the insulators can be a problem in the harsh chemical environment since they gradually become conductive and the battery self-discharge rate increases.

Figure 3-1. NaS Battery Case and Cell.
During discharge, as positive Na\(^+\) ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 volts. The reaction process is reported:

\[
2\text{Na} + x\text{S} \xrightleftharpoons{\text{CHARGE}} \text{Na}_2\text{S}_x \quad E_0 \approx 2\text{V} @ 300^\circ\text{C} \quad (3-1)
\]

This process is reversible as charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium as depicted in Figure 3-2. The battery is kept at approximately 300\(^\circ\)C and is operated under conditions such that the active materials at both electrodes are liquid and the electrolyte is solid.

Very similar to the previous technology is the Sodium Metal Chloride battery: both batteries operate at relatively high temperatures, both use a negative electrode composed of liquid sodium and both use a \(\beta\)-alumina solid electrolyte to separate this electrode from the positive electrode. However, Sodium Metal Chloride cells include a secondary electrolyte of molten sodium tetrachloroaluminate (NaAlCl\(_4\)) in the positive electrode section and an insoluble transition metal chloride (FeCl\(_2\) or NiCl\(_2\)) or a mix of such chlorides, as the positive electrode. The molten salt electrolyte (often referred to as a *melt*) serves to conduct sodium ions from the solid electrolyte to the metal chloride reaction site.
The overall chemistry of these cells, during normal operation can, for nickel or iron monometallic cathodes, be summarized as:

\[
\begin{align*}
\text{CHARGED} & \quad \text{DISCHARGE} & \quad \text{DISCHARGED} \\
\text{FeCl}_2 + 2Na & \rightleftharpoons Fe + 2NaCl & E_0 = 2.35 \text{V @ 250°C} \quad \text{(3-2)} \\
\text{NiCl}_2 + 2Na & \rightleftharpoons Ni + 2NaCl & E_0 = 2.58 \text{V @ 300°C} \quad \text{(3-3)}
\end{align*}
\]

The site of reaction in the positive electrode section of the cell proceeds toward this electrode’s core, starting from the interface between it and the solid electrolyte. At the beginning of discharge, cell resistance is at its minimum, and sodium ions from the β-alumina are conducted by the melt to reaction sites at what is essentially the surface or front of the electrode, adjoining the β-alumina. For a Nickel Chloride cell the reaction proceeds with the NiCl₂ being reduced to metallic Ni, and with the formation of NaCl. As the discharge continues, the reaction zone migrates deeper into the electrode section, toward the current collector and away from the β-alumina. Electrons are carried from the current collector to the reaction site via pathways of electrically conductive metallic nickel created as the reaction proceeds.

The Sodium Nickel Chloride batteries are also known with the commercial name ZEBRA (see Figure 3-3). Zebra cells are sometimes regarded as sodium sulfur cells in which the sulfur has been replaced with nickel or iron. This is in some aspects true, but substituting chlorinated nickel or iron in the positive electrode has profound safety impacts.

Figure 3-3. ZEBRA battery Case and Cell.
Much of the challenge of creating safe NaS cells derives from the immense need to prevent contact between the sulfur and sodium electrodes, since these substances react violently [38]. This is the main reason why ZEBRA batteries are very interesting for mobility application [39], [40], although the NaS still remains an interesting technology for stationary applications. The working temperature is very alike the previous one as well as the thermal management. Thus from an electrical modelling perspective a model suited for the ZEBRA can be easily fitted for studying a NaS one.

A module with nominal power 17.8 kW and nominal energy 17.8 kWh [41], currently under installation, at the ENEL Ingegneria Innovazione test facility in Livorno, is shown in Figure 3-4.

3.1.2 Flow Battery

Flow batteries allow storage of the active materials external to the battery and these reactants are circulated through the cell stack. The first such battery was the Zinc Chlorine battery in which the chlorine was stored in a separate cylinder. It was first used in 1884 by Charles Renard to power his airship La France which contained its own on board chlorine generator. The technology was revived in the mid 1970s.

They differ from a conventional battery in two ways:

- the reaction occurs between two electrolytes, rather than between an electrolyte and an electrode,
they store the two electrolytes external to the battery and the electrolytes are circulated through the cell stack as required.

The great advantage that this system provides is the almost unlimited electrical storage capacity (MWh), the limitation being only the capacity of the electrolyte storage reservoirs. Flow batteries are essentially comprised of three key elements:

1) cell stacks, where power is converted from electrical form to chemical form,
2) tanks of electrolytes where energy is stored,
3) circulating and control systems.

An individual cell consists of a negative electrode and a positive electrode separated by an ion exchange membrane. The battery uses electrodes that do not take part in the reactions but merely serve as substrates for the reactions. There is therefore no loss of performance, as in most rechargeable batteries, from repeated cycling causing electrode material deterioration. Banks of these cells can then be linked together to create a bipolar module ‘cell stack’ where the electrodes are shared between the adjacent cells, with the cathode of the first cell becoming the anode of the next cell, etc. Linked in series, sufficient cells in a string can then form the desired voltage for the cell stack, shown in Figure 3-5 [42].

During operation, the two electrolytes flow from the separate storage tanks to the cell stack for the reaction, with ions transferred between the two electrolytes across the ion exchange membrane; after the reaction, the spent electrolytes are returned to the storage tanks. During recharging, this process is reversed.

In pure flow batteries it is claimed that the solid electrodes inert and do not directly take part in the chemical reaction taking place in the two half cells, so that they are not consumed or degraded (or at least degraded only very slowly) by the chemical reaction occurring in the liquid electrolytes. For this reason flow batteries can potentially have very long cycle life,
compared to other kinds of batteries. However, one problem with flow batteries is that the ion exchange membranes are not completely impermeable to the species of ions which are supposed to be separated so that over time some amount of cross contamination of the electrolytes in the two half cells occurs, thus degrading performance. This degradation can be fixed by periodically replacing the electrolyte which adds to the ongoing maintenance cost of the batteries. Vanadium Redox Batteries (VRB) get around this cross contamination problem by using different charge states of vanadium ions in the two half cells. In this case cross contamination slightly degrades the energy efficiency but does not lead to performance degradation.

The VRB system is reported in Figure 3-6: the fuel cell stack, where the oxidation-reduction reaction is realized; two tanks where the Vanadium solutions are stored; and the circulating system (pumps and pipes). In the right picture there are samples of the Vanadium solutions in the different oxidation states.

![Figure 3-6. Concept diagram of a VRB and Vanadium solutions (from left to right $V^{2+}; V^{3+}; V^{4+}; V^{5+}$).](image)

The total power available is related to the electrode area within the cell stacks, while the total storable energy is function of the tanks volume and of the electrolyte concentration. The cells have a current density around 0.1 A/cm$^2$. Separate reactions occur in each half-cell. During discharge, electrons are produced in the reaction in the negative half-cell and are consumed in the reaction in the positive half-cell, forming the basis for an electrical current.

In the negative half-cell during discharge, vanadium (II) ions in solution are converted to vanadium (III) ions, with the loss of an electron which is available for conduction:

$$\text{CHARGED \ DISCHARGED} \begin{align*} V^{2+} & \rightleftharpoons V^{3+} + e^- \end{align*} \quad E_0 = -0.255V \quad (3-4)$$

In the positive half-cell during discharge, vanadium (V) ions are converted to vanadium (IV) ions, gaining an electron in the process:
The overall equation is:

\[
\begin{align*}
\text{CHARGED} & : \quad VO_2^+ + e^- + 2H^+ \rightleftharpoons VO^{2+} + H_2O & E_0 = 1.000V \\
\text{DISCHARGE} & : \quad VO^{2+} + H_2O \rightleftharpoons \ begun{array}{c} \text{DISCHARGED} \ \end{array} & (3-5)
\end{align*}
\]

Hydrogen cations are consumed in the process, which means that the pH of the positive electrolyte can be expected to change over time. To maintain charge balance within the half-cells, there must be a mechanism for the transit of hydrogen ions from the negative half-cell to the positive half-cell, which is generally accomplished by placing an ion-conducting membrane between the two.

A module with nominal power 10 kW and nominal energy 100 kWh [43], currently under installation, at the ENEL Ingegneria Innovazione test facility in Livorno, is shown in Figure 3-7.

![Figure 3-7. VRB Battery (Courtesy of ENEL Ingegneria e Innovazione).](image-url)
3.1.3 Technologies costs comparison

A brief comparison of the relevant characteristics of the two technologies is reported in Table 3-1. The data reported for the energy and power density are taken from the datasheet of the module previously shown. The VRB full system, shown in Figure 3-7, weighs about 10000 kg, and the Vanadium solutions count for about the 65%. In the ZEBRA system only the module shown Figure 3-3, whose weight is about 182 kg, is accounted for the evaluation of the weight instead. It has to be noted that fixed costs, such as projection and installation, are not considered in the table and can count for about 20% of the overall cost. The conversion system of the VRB (the PCS) is already considered in the specific cost while it has been estimated for the ZEBRA. Concerning the life of the storage it is assumed that after the expected charge/discharge cycles number and after the declared life-time the battery will still possess, at least, 80% of its nominal capacity.

<table>
<thead>
<tr>
<th></th>
<th>VRB</th>
<th>ZEBRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Energy Density</td>
<td>15 Wh/kg (only tanks)</td>
<td>100 Wh/kg</td>
</tr>
<tr>
<td></td>
<td>10 Wh/kg (full system [43])</td>
<td>(only battery no PCS [41])</td>
</tr>
<tr>
<td>Gravimetric Power Density</td>
<td>50 W/kg (only cells)</td>
<td>160 W/kg</td>
</tr>
<tr>
<td></td>
<td>1 W/kg (full system [43])</td>
<td>(only battery no PCS [41])</td>
</tr>
<tr>
<td>Expected Charge/Discharge cycles and calendar life</td>
<td>1,000 cycles per year for 15 years [42]</td>
<td>1,000 cycles per year for 5 years [38]</td>
</tr>
<tr>
<td>Present Specific Cost (specific power cost + specific energy cost)</td>
<td>2.3 $/W + 0.3 $/Wh (year: 2007 [42])</td>
<td>0.5 $/W* + 0.24 $/Wh (for 10,000 units/year [41])</td>
</tr>
<tr>
<td>Future Specific Cost (specific power cost + specific energy cost)</td>
<td>1.2 $/W + 0.2 $/Wh (year: 2013 [42])**</td>
<td>0.3 $/W* + 0.1 $/Wh (for 100,000 units/year [41])**</td>
</tr>
</tbody>
</table>

Table 3-1. Comparison table for the two technologies (note: * estimated cost for the PCS, VRB’s PCS already included in the specific power cost; ** EPRI source for VBR, Manufacturer source for ZEBRA)

It is now interesting to obtain an evaluation of the energy cost for the two technologies. Firstly the SOC cycle (or equivalent SOC cycle) is defined as the amount of energy that can be charged or discharged. Its value is equal to the nominal energy value of the storage. Thus an ideal charge from SOC level 0 to SOC level 1 means one SOC cycle. Similarly a charge from SOC level 0.5 to full charge and back to 0.5 means one SOC cycle. It is worth noting that the charge/discharge cycle number declared by the manufacturer is referred to a 80% discharge intensity, that means a full charge and discharge goes from 0.2 SOC level to 1 and back to 0.2 corresponding thus to a 1.6 SOC cycles.

The specific power and energy costs (respectively $P_c$ and $E_c$) are the one previously considered and moreover also the fixed costs (i.e. the 1.2 multiplier) are taken in account:
The $P_c$ mainly depends on the size of the PCS. It is very important to design the size in order to have it performing correctly the right service. For example, the ZEBRA battery could release a power at least equal to its energy (i.e. 17.8 kW for the module above considered of 17.8 kWh); however, depending on the task, the PCS can be downsized thus reducing the cost.

The analysis here performed is done considering for both the storages 10 MWh nominal energy size, but 1.08 MW nominal power for the VRB and 4 MW for the ZEBRA. These sizes will be the one considered in the system studies with battery and wind generation coupled. Finally the specific energy cost is calculated as the ratio between the capital cost and the total energy that the storage is declared to manage without significant aging (i.e. the nominal SOC cycle per the nominal energy) and the average roundtrip efficiency. This last parameter takes in account the fact that the energy, flowing inside and then outside the battery, will be subject to the internal Joule losses and the PCS efficiency; the more intense are the charge and the discharge (i.e. the greater the power) the higher the losses. Of course the models proposed, can evaluate this kind of losses for the specific missions and thus estimate the roundtrip efficiency. A first evaluation however is done considering the nominal battery efficiency, estimated by the simulated mission at the end of the chapter. The ZEBRA battery system has a global efficiency (considering the Joule losses, the aux consumption and the PCS efficiency) around 90% per flow, that means 81% roundtrip efficiency. The VRB battery system presents a lower efficiency, about 80% per flow (meaning a roundtrip efficiency around 64%):

$$\text{Energy\_Value} = \frac{\text{Capital\_Cost}}{(\text{SOC\_Cycles}\times\text{Nominal\_Energy})/\text{Roundtrip\_Eff.}}$$  \hspace{1cm} (3-8)

A further correction requires the time length of the investments. It has to be considered, in fact, that the investment for the ZEBRA must be repaid in 5 years while for the REDOX in 15 years. The specific energy costs needs then an actualization in order to consider the two different investment time-horizon.

$$\text{Actualized\_Energy\_Value} = \text{Energy\_Value} \times [(1+i)^y].$$  \hspace{1cm} (3-9)

Where:

- $i$ is the discount rate (assumed 5%)
- $y$ is the number of years for the return of the investment (5 for the ZEBRA and 15 for the VRB)

Table 3-2 reports the results of the economic evaluation. It can be appreciated that, despite of its higher capital cost, the longer life grants, at the present, the VRB to be more cost effective.
of the ZEBRA. The costs still result higher compared to the actual energy generation costs, however, if the forecasted future costs reveal to be true and if a slight improvement in the battery life (especially for the ZEBRA) is achieved, then the electrochemical storage can be the ultimate solution to help the integration of massive amounts of wind energy and renewable energy.

<table>
<thead>
<tr>
<th>Nominal size (Power – Energy)</th>
<th>VRB</th>
<th>ZEBRA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.08 MW – 10 MWh</td>
<td>4 MW – 10 MWh</td>
</tr>
</tbody>
</table>

| Present specific costs               | 2.3 $/W + 0.3 $/Wh    | 0.5 $/W + 0.24 $/Wh    |
| Future specific costs                | 1.2 $/W + 0.2 $/Wh    | 0.3 $/W + 0.1 $/Wh     |

| Present capital cost                 | 6,360,000 $ (= 4,711,000 €)* | 5,280,000 $ (= 3,911,000 €)* |
| Future capital cost                  | 3,840,000 $ (= 2,844,000 €)* | 2,640,000 $ (= 1,955,000 €)* |

| Nominal charge/discharge cycles      | 15,000                | 5,000                  |
| SOC cycles                           | 24,000                | 8,000                  |

| Roundtrip Efficiency                 | 64% (80% per flow)    | 81% (90% per flow)     |

<table>
<thead>
<tr>
<th>Present values in $/€*</th>
<th>VRB</th>
<th>ZEBRA</th>
<th>VRB</th>
<th>ZEBRA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not actualized</td>
<td>Not actualized</td>
<td>Actualized</td>
<td>Actualized</td>
</tr>
<tr>
<td>Present energy value in $ (not actualized/actualized)</td>
<td>4.1 c$/kWh</td>
<td>8.1 c$/kWh</td>
<td>8.6 c$/kWh</td>
<td>10.4 c$/kWh</td>
</tr>
<tr>
<td>Present energy value in € (not actualized/actualized)</td>
<td>2.3 c€/kWh</td>
<td>4.1 c€/kWh</td>
<td>6.4 c€/kWh</td>
<td>7.7 c€/kWh</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Future values in $/€*</th>
<th>VRB</th>
<th>ZEBRA</th>
<th>VRB</th>
<th>ZEBRA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not actualized</td>
<td>Not actualized</td>
<td>Actualized</td>
<td>Actualized</td>
</tr>
<tr>
<td>Future energy value in $ (not actualized/actualized)</td>
<td>2.5 c$/kWh</td>
<td>4.1 c$/kWh</td>
<td>5.2 c$/kWh</td>
<td>5.2 c$/kWh</td>
</tr>
<tr>
<td>Future energy value in € (not actualized/actualized)</td>
<td>1.9 c€/kWh</td>
<td>3.0 c€/kWh</td>
<td>3.8 c€/kWh</td>
<td>3.9 c€/kWh</td>
</tr>
</tbody>
</table>

Table 3-2. Specific energy costs (note: *change rate assumed 1.35 $ per 1 € - January 2011).


3.2 Storage model description

3.2.1 Main assumptions

The storage model proposed and developed is suited for electrical studies and it has a general validity [44], [45], [46]. It can be parameterized for different chemistry and it has been detailed with the best availability of information [47], [48], [49], [50], [51].

The modelled dynamics regard the State-of-Charge (SOC) behaviour, the electrochemical conversion and the thermal characterization. The main state variables are therefore the state of charge, the temperature and the voltage: all the characteristic elements of the storage system (as open circuit voltage, internal resistances, limitations and protections thresholds) present some kind of dependence from these state variables. Therefore the relationships among them are highlighted further on. An overview of the electrical equivalent of the abovementioned dynamics of the equivalent cell is proposed in Figure 3-8.

![Figure 3-8. Electrical equivalent of the main dynamics analyzed for the description of the storage.](image)

The batteries are composed by a series and a parallel of different cells and to increase the size of the system a further parallel of units is realized. It is assumed that all the units are perfectly balanced and thus the tasks requested to the storage system are equally divided among them. Under this assumption all the dynamics are built in the single equivalent battery; the overall storage desired size is then obtained by multiplying/dividing the battery parameters for the number of series/parallel elements. As foretold the two battery models are very similar, however, regarding the VRB, due to lack of information about the thermal properties, the thermal dynamic is not present. In order to provide a thermal capability (thus to study and perform overloads), an equivalent thermal dynamic based on the Joule integral has been
implemented. A proper description is done in the limitation paragraph. The Simulink block diagrams, depicted in Figure 3-9 and Figure 3-10, implement the relationships of these dynamics.

Figure 3-9. Block diagram of the ZEBRA model.

Figure 3-10. Block Diagram of the VRB model.
As it can be appreciated the two models are very similar, the VRB’s one, as foretold, lacks of
the thermal dynamic. The main differences occur in the proper parameters inserted in the
specific blocks. The diagrams can be easily understood reading it from the upper left to the
lower right. The model input is the active power reference, Pref (in pu or in W), it means the
power that the battery is asked to release or to store.
This reference is passed through the limitations system, whose duty is to limit the power
transit; the limit thresholds depend on the power that the conversion system is allowed to
manage. After that a further limitation is applied, the power reference is translated into a
current reference (in pu) and this reference is limited depending on the maximum current that
is allowed to flow in the cell. This translation from power reference to current reference is
done by the knowledge of the battery voltage (in V). The output of this first block is thus the
reference current limited (in pu).
This reference is used by the current control, along with the actual flowing battery current, to
set the reference voltage that the BMS has to impose to the battery connection points. The
voltage reference is the input for the electrochemical circuit block. Inside this block the
relationships that characterize the internal specific cell behaviour are stored. Because some of
the characterizing parameters, such as open voltage circuit and internal resistances, can be
function of the SOC or of the cell temperature (°C), their knowledge is required. The main
output of the electrochemical block are the current (in A and in pu), the output power (W) and
the joule losses (W).
The SOC value (in pu) is calculated, in the state-of-charge block, by means of the electrical
current integration. In the Redox the SOC block includes the self-discharge evaluation due to
the fact that when the solutions are circulating through the cell stack, there are leakages
across the cells. For both the systems there are no stand alone self discharge and the capacity
level (i.e. the nominal capacity) does not change during the time (there is no aging) and it does
not change with the current intensity (i.e. no Peukert’s effect taken in account).
The temperature is evaluated by the internal thermal dynamic, i.e. the algebraic sum of the
joule losses and of the thermal power removed by the cooling fan (or added by the heater),
known the thermal inertia and the thermal resistance of the battery case. As foretold in the
Redox the thermal dynamic is realized through an equivalent thermal based on the Joule
integral.
In the ZEBRA, the auxiliary system provides the control and the evaluation of the thermal
contribution by the cooling fan and by the heater. It requires the knowledge of the
temperature to trigger them and also of the SOC because the maximum cell temperature
allowed varies with the charge level. For the Redox there is no cooling system, but there are
the circulating pumps. In this case the block contains the equations to evaluate the pumps
consumption, function of the flowing electrical current, which depends on the vanadium
solutions flow. It has to be noted that no dynamic for the solution flows is considered, that because the current, produced by the cell, is linearly dependant on the flow.

There is a protections system that forces to zero the reference current whenever the SOC level reaches the maximum value allowed (generally 1 pu) and a further charge is required, the protection is untriggered when a discharge is required. On the contrary when the SOC level is at its minimum (for example 0.2 pu) and a discharge is required the system is blocked until a charge is commanded. For the ZEBRA, due to the necessity to be always turned on, thus with, at least, an internal temperature of 270°C, there is a further protection signal that forces a charge whenever the battery is at its minimum SOC and otherwise it would not be able to feed the heater to warm up.

At last there is the inverter efficiency block that computes the inverter losses and the auxiliary consumption that are to be taken from the output power. The battery power is the power just produced (or adsorbed) by the battery alone, the output power is the power that flows outside (or that flows inside) the complete storage system instead.

Table 3-3 reports the main information concerning the batteries modelled and analyzed [41],[43]. These batteries are used as a benchmark to choose the model parameters; the simulations in this chapter are intended to evaluate the behaviour of the single battery here reported.

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL nominal data</td>
<td>Voltage (V)</td>
<td>2.58</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Current (A)</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Capacity (Ah)</td>
<td>32</td>
<td>Independent</td>
</tr>
<tr>
<td></td>
<td>Power (W)</td>
<td>82.6</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Energy (Wh)</td>
<td>82.6</td>
<td>Independent</td>
</tr>
<tr>
<td></td>
<td>Max current in charge-discharge (A) / (pu)</td>
<td>62 A / 2 pu</td>
<td>80 A / 2 pu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>96 A / 3 pu</td>
<td>80 A / 2 pu</td>
</tr>
<tr>
<td>BATTERY nominal data</td>
<td>Cell Configuration (#S - #P)</td>
<td>108 S ÷ 2 P</td>
<td>40 S ÷ (2+2+1) P</td>
</tr>
<tr>
<td></td>
<td>Voltage (V)</td>
<td>278.6</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Current (A)</td>
<td>64</td>
<td>200 (80+80+40)</td>
</tr>
<tr>
<td></td>
<td>Capacity (Ah)</td>
<td>64</td>
<td>1850</td>
</tr>
<tr>
<td></td>
<td>Power (kW)</td>
<td>17.8</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>Maximum Power (kW) / (pu)</td>
<td>30 kW / 1.7 pu</td>
<td>15 kW / 1.4 pu</td>
</tr>
<tr>
<td></td>
<td>Energy (kWh)</td>
<td>17.8</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Usable energy (kWh)</td>
<td>14.2</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>SOC range (pu)</td>
<td>0.2 ÷ 1 (80%)</td>
<td>0.2 ÷ 1 (80%)</td>
</tr>
</tbody>
</table>

Table 3-3. Cell and Batteries nominal data.
The storage system used in the coupled system with the wind turbines will be composed by a set of these batteries. Table 3-4 reports an overview of the data. As foretold two storage sizes are chosen in order to have the same nominal energy. The powers differ, in the case of VRB because the PCS size is bound to the cell stacks nominal power, while in the ZEBRA the PCS could be designed for the overall nominal power (10 MW) but, depending of the task required, it could result oversized.

<table>
<thead>
<tr>
<th>Dynamic Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: ZS-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery configuration (# units)</td>
<td>560</td>
<td>100</td>
</tr>
<tr>
<td>Nominal Energy (Wh)</td>
<td>10,000 kWh</td>
<td>10,000 kWh</td>
</tr>
<tr>
<td>Storable Energy (Wh)</td>
<td>8,000 kWh</td>
<td>8,000 kWh</td>
</tr>
<tr>
<td>Nominal Power (W)</td>
<td>10,000 kW</td>
<td>1,080 kW</td>
</tr>
<tr>
<td>PCS Power (W)</td>
<td>4,000 kW</td>
<td>1,500 kW</td>
</tr>
</tbody>
</table>

Table 3-4. System data.

The rest of the paragraph develops as follows:

- Limitations
- State-Of-Charge
- Electrochemical dynamic
- Current control loop
- Thermal dynamic
- Auxiliary
- Protections
- Inverter efficiency

3.2.2 Limitations

The first blocks analyzed are the one related to the limited reference current. As foretold the input to this block is the same input to the model that is the reference power (PrefStorage). This value is firstly limited by the control on the maximum charging/discharging power (set by the PCS limits), the subsequent reference power is then translated in reference current in per unit by the division of the battery voltage (V_{battery}) and of the nominal cell current (I_{nom}) and then passed in a current limiter. From now the two blocks differs for two typologies.

**ZEBRA**

In the ZEBRA one, see Figure 3-11, the two limits are generated as follows:
The discharge current is function of the cell temperature: once the maximum allowed temperature is reached the current is limited from a 3 pu to 0.5 pu to avoid thermal runaway.

The charge current is limited by a first signal that reduces the current from 2 pu to 0.5 whenever the SOC reaches 0.8 pu: this emulates the commutation from fast charge towards slow charge (CC constant current to CV constant voltage). The charge can also be limited if the cell temperature reaches a specific value, function of the SOC. The battery, in fact, is not allowed, during a charge process, to overcome a certain temperature; this temperature is lower with the increase of the SOC (see Figure 3-12).

---

**Figure 3-11.** ZEBRA limitations block diagram.

**Figure 3-12.** Maximum allowed temperature during charge.

**VRB**

In the VRB, see Figure 3-13, the current limits are generated by the thermal equivalent.
The logic of this equivalent is quite simple: the heating of the cell is due to the internal losses that are assumed to be quadratic dependant from the current (Joule losses). It is assumed that the cell can bear a certain amount of overload (for example extra 0.8 pu current for 5 minutes each 10 minutes).

Chosen the bearable current for infinite time equal to 1.2 pu, the (positive) difference between the flowing current and this one gives the value of the overcurrent, $\Delta i$. The overcurrent integral gives an overload time value. If a certain threshold (equivalent to 192 seconds for these thresholds) is overcome then the limitation is triggered and the current is limited:

$$\int \Delta i^2 dt = \text{OverloadTime} \quad (3-10)$$

It has to be noted that this integral is derived by the classical Joule integral used, for example, as a designing criteria for the cables. In that case the result is an energy because it is the integral of the Joule losses ($Ri^2$, both in physical values). In this case the current integrated is a pu and the resistance is omitted because it is assumed that it is constant (and this is quite true for the VRB in the 0.4 ÷ 1 SOC range), thus the result is a pure time. The integral deputed to evaluate this overload is periodically (for example every 600 seconds) reset by the output of another counter triggered by a flip-flop set-reset.

It has to be noted that being this kind of approach quite unusual, a proper parameters tuning and accurate validation will be required in the real battery test.

Table 3-5 offers a summary of the previously described limitations strategies.
### Limitations parameters

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Limitations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast Charge: CC-CV (SOC)</td>
<td>@ 0.8 SOC: charge power reduced from 2 pu to 0.5 pu</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Maximum Temp. in Charge</td>
<td>SOC dependant: charge intensity reduced from 2 pu to 0.5 pu</td>
<td></td>
<td>Overload capability based on the cell thermal inertia (based on energy balance): max current 2 pu for 5 minutes each 10 minutes</td>
</tr>
<tr>
<td>Maximum Temp. in Discharge</td>
<td>@ 340 °C: discharge power reduced from 3 pu to 1 pu</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-5. Limitations parameters

#### 3.2.3 State-of-charge

This dynamic is related to the behaviour of the state of charge. This variable gives information about the quantity of energy still stored in the battery. Its value is 1 when the battery is fully charged and 0 when fully discharged. In both the technologies it is not recommended to go below 0.2.

The differential equation is shown further on: \( I_{dc} (A) \) is the current flowing in the battery and used by the auxiliary system; \( C \) is the nominal charge capacity, in Coulomb or Ah, of the battery:

\[
\begin{align*}
I_{dc} &= C \cdot \frac{dSOC}{dt} \\
SOC(0) &= SOC_0
\end{align*}
\]  

(3-11)

The ZEBRA has not auto-discharge, so no shunt/dissipative elements are considered. In case of need to model the self discharge, the previous equation is modified by the introduction of a resistive element, \( R \), as follows:

\[
\begin{align*}
I_{dc} &= \frac{SOC}{R} + C \cdot \frac{dSOC}{dt} \\
SOC(0) &= SOC_0
\end{align*}
\]  

(3-12)

In the VRB the solutions leakage across the cell has to be considered instead. Its value is about the 3% of the flowing current.

Another aspect that must be well kept in mind is that the SOC of a battery is not easily measurable most of the time. Its value is strictly related to the Open Circuit Voltage (OCV), as
depicted in the next section, but unfortunately the OCV measure is not available when in charge or in discharge. The problem of the estimation of the SOC is present in most typologies of battery except the VRB. It is, in fact, possible to have a single pilot cell separated from the main stack but that sees the same electrolyte solutions. In this way the measurement of the OCV and consequently of the SOC is quite easy. In the case of ZEBRA this is not possible; however, due to the absence of parasitic reaction (i.e. unitary cumbic efficiency) it is possible to evaluate the SOC by the simple integration of the flowing current (known the initial SOC). The measure of the current, though, is not error free, thus it is periodically necessary to perform a full charge in order to reset the error.

In the model, however, it is assumed that the SOC variable is perfectly known.

3.2.4 Electrochemical dynamic

To evaluate the amount of energy that is stored or released by the battery the electrochemical dynamic has to be detailed. A first order model takes into account two voltage generators with a resistor in series. The first one, $V_{oc}$, generates what is commonly known as open circuit voltage and its nominal value is generally function of the SOC. The controlled generator, $V_{battery}$, models the behaviour of the dc/ac converter. Its task is to close the circuit and set, by means of the current control system, the current value to have the desired value of power flowing in the circuit. The resistor, $R_0$, takes into account the internal Joule losses and can be function of SOC and of temperature. The current is assumed positive if it flows from $V_{oc}$ to $V_{battery}$ implying, hence, a discharge action.

A further step of characterization contemplates one or more RC chains, see Figure 3-14, in order to consider the time constants induced by the chemistry delays. Generally two time constants are sufficient [49]. By the measurement available (or by the estimation of some values in case of absence) two electrochemical circuits have been realized for each battery. The first one with just one resistive element, called $R_{cell}$, the second one with two RC chains (i.e. two time constants), respectively long time and short time, and the internal resistance, $R_0$.

![Figure 3-14. Electrochemical equivalent.](image-url)
The differential relationships are here reported (for a generic number ‘i’ of RC chains):

\[
\begin{align*}
I_{dc} &= I^i_c + I^i_r \\
I^i_r &= \frac{\Delta V^i_{dyn}}{R^i_{dyn}} \\
I^i_c &= C^i_{dyn} \frac{dV^i_{dyn}}{dt}
\end{align*}
\]

\[I_{dc} = \frac{(V_{oc} - \sum_i \Delta V^i_{dyn} - V_{battery})}{R_0} \quad 3-13\]

The more RC chain are considered, the higher gets the differential order of the equation.

Two models for each storage has been realized, the first one (called ZEBRA/VRB Static) that includes a first order electrochemical circuit with no RC chains, the second one (called ZEBRA/VRB Dynamic) that includes the third order model with thus two RC chains. A comparison between the static and the dynamic model will be performed in the simulation paragraph.

One problem, though, is to obtain the correct $R_{dyn}$ and $C_{dyn}$ values. The technical report [49] suggests the following procedure, based on the measurement done according to Figure 3-15.

\[\text{Figure 3-15. Typical voltage and current profiles during a constant current discharge.}\]

It is recommended to perform the measurement after the battery has been in a steady state for several hours and once the test has been completed ($\tilde{I}$) it is required to wait until the complete stabilization of the battery voltage:

- $V_{oc}$ can be easily measured directly from the connection points once the system is in steady state conditions. This is for the initial and for the final test voltages $V_0$ and $V_1$.

- $R_0$ can be determined by the measure of instantaneous drop voltages during the current steps and dividing them by the current themselves:
The sum $R_0 + R_{st}$ can be determined, after that the other parameters are known, by the evaluation of the drop on $R_0$, once the transitory of the two RC blocks are finished:

$$V_1 - V_3 = (R_0 + R_{st} + R_{lt}) \cdot \bar{I} \quad (3-15)$$

The time constants $\tau_{lt}$ and $\tau_{st}$ are determined by the minimization of the difference between the measured and the simulated response at $\bar{I}$, where the simulated response is:

$$V = V_3 - R_0 \bar{I} + R_{st} \bar{I} (1 - e^{-(t - \bar{I})/\tau_{lt}}) + R_{st} \bar{I} (1 - e^{-(t - \bar{I})/\tau_{st}}) \quad (3-16)$$

The different electrochemical characteristic values are hereafter analyzed.

**ZEBRA**

Firstly the Open Circuit Voltages (in V and in pu) in function of the SOC are reported in Figure 3-16. The voltage is quite constant and near the 1 pu (the base voltage is 2.58 V) until 0.4 SOC, after that it decreases until 2.35 V, this is due to the fact that the Fe substitutes the Ni in the reaction process.

![Figure 3-16. ZEBRA Open Circuit Voltage.](image-url)
The dependence of the resistance is not linear on the temperature and on the SOC. It can be noticed that the resistance increases with the decrease of the temperature, this fact must be kept in mind when setting the temperature thresholds that triggers the cooling fan.

The behaviour is reported in the mesh plots of Figure 3-17 and temperature parametrized in Figure 3-18. The pictures report both the resistances in physical value and in pu. The per unit system can be useful to compare the performances of different cell sizes and technologies. The resistance increases with the decrease of the SOC and of the temperature.

![Figure 3-17. ZEBRA Resistance (Mesh plot).](image1)

![Figure 3-18. ZEBRA Resistance (Temperature parametrized).](image2)

The resistance graphs reported refers to the value of the overall resistance, called \( R_{\text{cell}} \), in the case of no time constants in the electrical circuit.

The estimation of the values of \( R_{\text{ht}} \) and \( R_{\text{st}} \) is more complex and, while waiting for the execution of new test measurement, they have been estimated by the measurement done in [49]. Figure 3-19 (left picture) shows the behaviour (for a temperature of 300°C) of \( R_0 \), \( R_{\text{ht}} \) and \( R_{\text{st}} \) their sum.
$R_{\text{tot}}$ and for comparison $R_{\text{cell}}$ (@ 300 °C). It can be appreciated that the values of $R_{\text{tot}}$ and $R_{\text{cell}}$ are very similar.

For what regards the capacitance values, the quoted bibliography gives a time constant equal to 600 s for the long time and 6 s for the short time. Thus the capacitances are calculated as:

$$C = \frac{\tau}{R} \quad (3-17)$$

**VRB**

The OCV of the VRB is quite variable compared to the one of the ZEBRA instead. The potential is defined by the Nernst’s law:

$$V_{oc} = V^0 + \frac{R \cdot T}{F} \ln \left( \frac{c_{\text{V}^+}^\ast}{c_{\text{V}^+}} \cdot \frac{c_{\text{H}^+}^2}{c_{\text{H}^+}} \cdot \frac{c_{\text{e}^-}^\ast}{c_{\text{e}^-}} \right) \quad (3-18)$$

If it assumed that the product/ratio of the activity coefficients is equal to 1, the potential $V^0$ can be assumed equal to 1.255 V, which is the summation of negative and positive half-cell potential during discharge [52], [53], [54]. The overall potential depends on the concentration ratios, $c_i^\ast$, of the electrolytes in the two tanks and, due to the linear dependence between these concentrations and SOC, can be formulated as follows:

$$V_{oc} = V^0 + \frac{R \cdot T}{F} \ln \left( \frac{SOC}{1 - SOC} \cdot \frac{(SOC + 6)^2}{1 - SOC} \cdot \frac{SOC}{1 - SOC} \right) \quad (3-19)$$
Where $R$ (J/mol/K) is the universal gas constant, $F$ (C/mol) is the Faraday constant and $T$ (K) is the absolute cell temperature, assumed to be almost constant.

It ranges from 1.1 V at full discharge to 1.6 V at full charge (see Figure 3-20), showing thus a different behaviour from the ZEBRA, whose OCV was almost constant (see Figure 3-16). Even if the equilibrium voltage is 1.25 V, for sizing reason, a nominal voltage equal to 1.35 V, corresponding to the OCV of 50% SOC, has been assumed.

![Figure 3-20. VRB Open Circuit Voltage.](image)

The VRB cell resistance, depicted in Figure 3-21, is quite constant. As before the resistance graphs reported refers to the value of the overall resistance. The value is almost constant for SOC greater than 0.4; with the lowering of the SOC the resistance increase is quite pronounced.

![Figure 3-21. VRB Resistance.](image)

The dynamic values are reported in Figure 3-22. In this case there is some difference between $R_{\text{tot}}$ (i.e. the sum of $R_0$, $R_e$ and $R_{st}$) and $R_{\text{cell}}$ for SOC lower of 0.4. The other values are very similar and moreover quite constant. The time constants in this case value 60 s for the long time and 6 s for the short time and the capacitances are evaluated as before.

All the main parameters are summarized in Table 3-6.
Figure 3-22. VRB Cell Dynamic Values.

<table>
<thead>
<tr>
<th>Dynamic Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: ZS-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage: OCV (V)</td>
<td>SOC dependant (see Look-up table)</td>
<td>1.28 (@SOC 0.2) ÷ 1.6 (@SOC 1) / 51.2 ÷ 64.0</td>
</tr>
<tr>
<td>OCV Range: Cell / Battery (V)</td>
<td>2.33 (@SOC 0.2) ÷ 2.65 (@SOC 1) / 252 ÷ 286</td>
<td></td>
</tr>
<tr>
<td>OCV Range (pu)</td>
<td>0.90 ÷ 1.03</td>
<td>0.92 ÷ 1.14</td>
</tr>
<tr>
<td>Total Internal Resistance (mΩ)</td>
<td>$R_{\text{tot}} = R_{i} + m(SOC - SOC_{f})$</td>
<td>SOC dependant (see Look-up table)</td>
</tr>
<tr>
<td>Base Res. (= $V_{\text{nom}}/I_{\text{nom}}$: Rcell / Rbattery (mΩ))</td>
<td>80.6 / 4353</td>
<td>33.8 / 270</td>
</tr>
<tr>
<td>Resistance Range and Average: Cell / Battery (mΩ)</td>
<td>6.9 (@SOC 1 &amp; T= 360 °C) ÷ 26.8 (@SOC 0.2 &amp; T= 260 °C); Ave= 15.3 / 373 + 1447; Ave= 826</td>
<td>4.1 (@SOC 0.6) ÷ 6.0 (@SOC 0.2); Ave= 4.7 / 32.8 ÷ 48; Ave= 37.6</td>
</tr>
<tr>
<td>Resistance Range and Average (pu)</td>
<td>9% ÷ 33% – Ave= 19%</td>
<td>12% ÷ 18% – Ave= 14%</td>
</tr>
<tr>
<td>$R_{0}$ (mΩ)</td>
<td>SOC &amp; T dependant (see Look-up tables)</td>
<td>SOC dependant (see Look-up tables)</td>
</tr>
<tr>
<td>$R_{1}$ (mΩ) (long)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{2}$ (mΩ) (short)</td>
<td>1.9 (constant)</td>
<td></td>
</tr>
<tr>
<td>$T_{1}$ (s) (long time constant)</td>
<td>600</td>
<td>60</td>
</tr>
<tr>
<td>$T_{2}$ (s) (short time constant)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$C_{1} = T_{1}/ R_{1}$ (F)</td>
<td>600 / $R_{1}$</td>
<td>60 / $R_{1}$</td>
</tr>
<tr>
<td>$C_{2} = T_{2}/ R_{1}$ (F)</td>
<td>3158</td>
<td>6 / $R_{2}$</td>
</tr>
<tr>
<td>Shunt Losses</td>
<td>None</td>
<td>3% $I_{dc}$ (if working)</td>
</tr>
</tbody>
</table>

Table 3-6. Electrochemical parameters.
3.2.5 Current control loop

The control of the power output is demanded to the current control loop. The reference current is therefore compared with the current flowing in the battery system and the difference, the error, is the input for the PI (Proportional-Integral) controller. The output of the controller sets the values for the voltage source, which models the electronic converter; therefore the current flowing in the battery cells is evaluated by comparing this voltage with the open circuit voltage of the battery and by knowing the internal resistance. The integral action of the controller grants that the current error is zero in the steady state conditions. Figure 3-23 summarizes graphically what described.

The controller parameters, as well the voltage limits, for the two batteries are reported in Table 3-7. The voltage limit values result very important especially when high power performances are required. The higher is the power that has to be released (or stored) the greater has to be the difference from the OCV and the \( V_{\text{battery}} \). The reaching of some voltage values could, in fact, cause damage both to cell and to the PCS.

A time constant, called Voltage delay, has been inserted to take into account the delay introduced by the PCS (estimated with a time constant of 0.5 seconds).

![Figure 3-23. Block diagram of the battery control system.](image)

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Control Loop</td>
<td>PI Controller: ( kp + Ti ) (pu ÷ s)</td>
<td>5 ÷ 0.1</td>
<td>5 ÷ 0.1</td>
</tr>
<tr>
<td></td>
<td>Min ÷ Max Voltages allowed:</td>
<td>1.7 ÷ 3.1 / 184 ÷ 335</td>
<td>1.0 ÷ 1.7 / 40 ÷ 68</td>
</tr>
<tr>
<td></td>
<td>Cell / Battery (V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min ÷ Max Voltage (pu)</td>
<td>0.66 ÷ 1.20</td>
<td>0.74 ÷ 1.26</td>
</tr>
<tr>
<td></td>
<td>Voltage Time Delay (s)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Voltage Rate Limit (pu/s)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3-7. Current Control loop parameters.
3.2.6 **Thermal dynamic**

The ZEBRA requires a thermal management thus it needs of a cooling fan to remove excess heat and a heating device (a resistor) in order to take the battery at the required working temperature (at least 260 °C) and also to keep it hot whenever it is not working. The battery is thus equipped with these auxiliary systems (fans and heaters) in order to enable the control system to keep temperature within the allowed range.

This is the main drawback of the hot temperature battery, even if it has a good thermal shield, there are always 110 W\(_{th}\) (for the 17.8 kWh module considered) lost for natural cooling; if left in stand-by it would cool down to the local temperature (i.e. 25 °C) within 7 days. Even if it is working but the internal Joule losses are not sufficient to balance the thermal leakage, there is the need to dissipate some energy to keep it hot. As foretold the ZEBRA does not present any shunt losses such as other chemistry (lead acid or Lithium), though, the need to keep it hot can be considered as an equivalent parasitic loss.

The thermal dynamic is very crucial also when high power demand is required. This kind of management requires high currents thus leading to high thermal dissipation on internal resistance. This fact must be kept well in mind especially when the battery is used for mobile applications, whenever, in fact, the car is performing an acceleration or a regenerative braking, high amount of energy in few time are asked or pumped inside the battery and thus it is important to know the thermal inertia of the system and the thermal capability of the cooling fan.

A possible representation of the differential relationship is reported in Figure 3-24. Using the electric components, the differential equations, reported subsequently, can be easily understood.

![Figure 3-24. Thermal dynamic described by the mean of electric equivalent.](image)

If, in fact, it is assumed that the temperature, T (°C), behaves like the voltage and the thermal power, Q (W), like the current, then the capacitor and the resistor represents the thermal capacitance, \(C_T\) (J/K), and the thermal resistance, \(R_T\) (K/W), of the battery. The two current generators are used to model the thermal power generated by Joule effect, \(Q_{Pr}\), and the thermal contribution of both cooling fan and heater devices, \(Q_{Paux}\).
\[
Q_{Pr} + Q_{Pr} + Q_{R} = Q_{C}
\]

\[
Q_{R} = \frac{\Delta T}{R_{T}}
\]

\[
Q_{C} = C_{T} \cdot \frac{dT}{dt}
\]

\[
T(0) = T_{0}
\]

The values are reported in Table 3-8. As foretold, for the VRB it has been realized an equivalent thermal dynamic.

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: ZS-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Dynamic</td>
<td>Case Thermal Losses ($W_{th}$)</td>
<td>110 W ($T_{cell} = 300^\circ C$ &amp; $T_{env} = 25^\circ C$)</td>
<td>Cell thermal parameters unknown: Overload capability based on the equivalent thermal inertia</td>
</tr>
<tr>
<td></td>
<td>Case Thermal Time Constant ($3^*T = 3^*R_{th}^*C_{th}$)</td>
<td>168 h (= 604800 s) (time needed to get from 300°C to 25 °C ±5% if shut down)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Case Thermal Resistance $R_{th}$ (K/W)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Battery Thermal Capacitance $C_{th}$ (J/K) ($C_{th} = 3^*T/3^*R_{th}$)</td>
<td>80640</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature Working Range (°C)</td>
<td>Minimum: 260 °C Maximum: SOC dependant</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-8. Thermal dynamic parameters.

### 3.2.7 Auxiliary systems

**ZEBRA**

The evaluation of the power removed by the fan or given by the heater is done in this block. The control turns on the fan whenever the cell temperature is above the threshold reported in Figure 3-25. The heater is turned on if the temperature gets below to 260 °C and is inserted until the temperature goes above 270 °C.

To model the thermal power removed by the fan it has been supposed a convective coefficient value of 30 W/K, which, assuming a delta temperature of 300 °C between the cold air and the cell, means a removed power of about 9000 $W_{th}$. 


This value is quite reasonable because the Joule losses can be assumed equal to 3400 W if the nominal battery current is released (with a SOC around 0.5 and a temperature of about 300 °C) and of course 4 times if the current doubles. The thermal power value estimated for the fan is thus quite reasonable because its value avoid thermal runaway in case of nominal current. The consumption of the BMS, which counts for about 10 W, has also been considered [41].

**VRB**

The main auxiliary systems in the VRB are the circulating pumps. As a rule of thumb [51] their consumption can count for about 15% of the nominal capacity (in kWh) in 24h. For the 100 kWh VRB considered that leads to a nominal consume of about 625 W (i.e. the 6% of the nominal power). It is moreover assumed that the pumps are inverter driven thus it is reasonable to expect a linear relationship between the consumption and the flow (and thus the current).

The BMS consume is higher compared to the ZEBRA and is about 1% of the nominal power.

Table 3-9 summarizes the parameters for the two technologies.

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Battery Management System consume (W)</td>
<td>10 (&lt; 0.1% $P_{\text{nom}}$)</td>
<td>100 (= 1% $P_{\text{nom}}$)</td>
</tr>
<tr>
<td><strong>Auxiliary Systems</strong></td>
<td>Electric Power Auxiliary Consume (for Battery)</td>
<td>Cooling Fan: 60 W (&lt; 0.4% $P_{\text{nom}}$) (temperature threshold see figure)</td>
<td>Circulating pumps: 15% Battery kWh capacity/24h → 625 W (= 6% $P_{\text{nom}}$) (note: pumps inverter driven → the consume is α to the Vanadium flow → α Current, see Look-up Table)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heater: 190 W (= 1% $P_{\text{nom}}$) (temperature threshold 260 °C)</td>
<td></td>
</tr>
</tbody>
</table>
3.2.8 Protections

The battery control system has the main task to stop the battery if the SOC level approaches 0.2 or 1. It forces to zero the reference current whenever the SOC level reaches the maximum value allowed (generally 1 pu) and a further charge is required; the protection is unblocked when a discharge is required. On the contrary when the SOC level is at its minimum (for example 0.2 pu) and a discharge is required the system is blocked until a charge is commanded. For the ZEBRA, due to the necessity to be always available and thus with an internal temperature of 270°C at least, there is a further protection signal that forces a charge whenever the battery is at its minimum SOC and otherwise it would not be able to feed the heater to warm up.

Table 3.9. Auxiliary system parameters.

<table>
<thead>
<tr>
<th>Dynamic Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling fan thermal power (based on the convective heat transfer coefficient)</td>
<td>Convective Coeff. 30 W/K → hp ΔT = 300°C → removed thermal power = 9000 Wth (note: @ I= 64 A &amp; R_{tot}= 0.826 Ω → P_{joule}= 3400 Wth @ I= 128 A &amp; R_{tot}= 0.826 Ω → P_{joule}= 13500 Wth)</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 3.10. Protections parameters.

<table>
<thead>
<tr>
<th>Dynamic Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protections</td>
<td>Maximum Charge (SOC) 1</td>
<td>1</td>
</tr>
<tr>
<td>Minimum Charge (SOC)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Minimum Temperature &amp; Minimum SOC</td>
<td>Charge requested if: SOC &lt; SOC_{min} &amp; T &lt; T_{min} (energy needed for heater)</td>
<td>None</td>
</tr>
</tbody>
</table>
3.2.9 **Inverter efficiency**

The evaluation of the output battery from the storage system is done in this last block, shown in Figure 3-26. The $P_{\text{battery}}$ signal is passed through the PCS efficiency blocks; it is divided in two signals because if a charge is performed the $P_{\text{battery}}$ is multiplied with the reciprocal of the PCS efficiency. In case of discharge the PCS efficiency multiplies the $P_{\text{battery}}$. The consumption of the auxiliary systems is then subtracted and the value of $P_{\text{output}}$ ($P_{\text{output}}$, like $P_{\text{battery}}$, is positive in case of discharge and negative in case of charge) is calculated.

![Figure 3-26. Inverter efficiency block diagram.](image)

3.3 **Storage model testing simulations**

3.3.1 **Benchmark mission**

As foretold the first simulation provides an analysis, by means of a series of charge/discharge cycles, of the response of the single batteries models. Thus the 17.8 kW - 17.8 kWh ZEBRA and the 10 – 100 kWh VRB are now tested. The proposed mission is shown in Figure 3-27. It is expressed in pu values referred to the respective battery base power (note that the VRB base power is 10.8 kW, while the ZEBRA base is 17.8 kW): it consists in a first period of 10 minutes rest, followed by a charge at nominal power (-1 pu) for 40 minutes, then a discharge at different intensity (until the 80th minute). At last a fast charge (-2 pu) is done for 10 minutes followed by a final discharge at 1 pu.

It is to be noted that for each storage model a comparison between the model that includes the first order electrochemical circuit (called **Static Model**) and the third order circuit (the **Dynamic Model**) is performed during the simulations.
The two ZEBRA batteries begin the mission from a 60% SOC level and cell temperature of 300 °C. The first graph of Figure 3-28 reports the behaviour of the output (or input) power of the two ZEBRA batteries and for comparison the proposed mission to see if the batteries have succeeded. To better understand the stopping that happens the SOC graph is reported below. For example it can be seen at the 47th minute that the SOC reaches 1 (in both the models) and thus the protection system triggers the stop until a discharge is requested (at the 50th minute).

At the 24th minute the SOC reaches 0.8 thus the limitation system changes the maximum current charge intensity from 2 pu to 0.5 pu. At the 60th minute a deep discharge is requested and it can be appreciated that both the models are able to follow the reference; this time the
limitation is due to the voltage limit set by the current controller (see Figure 3-29). Also further
on (75th min), even if the discharge required is less intense the models cannot provide the
required power, this is due again to the voltage limit and by the fact that the SOC is getting
near the minimum and thus the internal resistance (and thus the voltage drop) is increasing.
The mission finishes with a charge and a subsequent discharge that cannot be completed due
to minimum SOC protection.

The main differences between the two models can be appreciated in the next graphs (Figure
3-29) related to the electrochemical variables: OCV (V), \(V_{\text{battery}}\) (V) and \(I_{dc}\) (A). With abuse of
notation the OCV Dynamic is the voltage that comprehends also the voltage drops on the two
RC chains. The “true” OCV is of course the same for both the ZEBRA models. The presence of
the capacitances gives to the Dynamic version of the model a kind of inertia due to the fact
that, for example, during a discharge the capacitances release, for a while, energy and the
overall internal resistance is lower compared to the Static model.

![Figure 3-29. ZEBRA OCV and battery voltages; Battery current.](image)

Figure 3-30 and Figure 3-31 report the main information concerning the thermal behaviour.
The temperature (second graph of Figure 3-30) is the result of the balance between the Joule
losses (positive values of both graphs of Figure 3-31; note that in this picture the results are
separately presented for the Static and the Dynamic model) and the auxiliary thermal power.
In this case, due to need of cooling the system, only the fans are working (negative values).
It can be appreciated that when the battery is idling (i.e. no power flowing) the temperature
slightly decreases because of the shield thermal losses. The cooling fan threshold is set in order
to cool the battery just what is sufficient to take its temperature far from dangerous values,
however, as soon the temperature is safe again the fans are shut down to avoid excessive cooling.

![Output and Reference Power](image)

![Battery Temperature](image)

Figure 3-30. ZEBRA Output and reference power (in kW); Battery Temperature.

Note that when the power required is almost near 2 pu (60th minute) the Joule losses are greater than the thermal power removed by the fans; the temperature keeps increasing with a rate that is determined by the thermal power surplus and by the system thermal inertia. The maximum temperature acceptable increases with the lowering of the SOC, after the 70th minute (i.e. SOC lower than 0.5), for example, the battery is allowed to have a cell temperature above 320 °C, according to the characteristic shown in Figure 3-12. The last graph, Figure 3-32, reports the SOC profiles realized and the cumulative work done expressed in number of SOC cycles.

Table 3-11 reports at last a summary of the most significant measurement. The battery work is the sum (without sign) of the energy stored and released. This value can be used to calculate the number of SOC cycles by the division with the nominal energy. The Joule losses and the auxiliary energy are also computed and used to evaluate the efficiencies. Three efficiencies are calculated: the first one takes just into account the internal battery losses, the second one includes the consumption of the auxiliaries (i.e. fans and heaters or pumps for the VRB) and the last one, the ultimate efficiency, includes also the PCS performance.
The efficiencies are around 80% for the dynamic and 75% for the static models. The dynamic one presents reduced Joule losses because of the minor equivalent resistance of the electrochemical circuit.
<table>
<thead>
<tr>
<th></th>
<th>Battery work (Wh)</th>
<th>Energy stored (Wh)</th>
<th>Energy released (Wh)</th>
<th>Joule losses (Wh)</th>
<th>Aux energy (Wh)</th>
<th>Efficiency w/o aux &amp; PCS</th>
<th>Efficiency w/o PCS</th>
<th>Efficiency ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEBRA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static</td>
<td>24090</td>
<td>11877</td>
<td>12213</td>
<td>6526</td>
<td>45</td>
<td>78.7%</td>
<td>78.6%</td>
<td>74.7%</td>
</tr>
<tr>
<td>Dynamic</td>
<td>25809</td>
<td>12562</td>
<td>13247</td>
<td>4624</td>
<td>40</td>
<td>84.8%</td>
<td>84.7%</td>
<td>80.5%</td>
</tr>
</tbody>
</table>

Table 3-11. ZEBRA mission summary result.

**VRB**

Also the VRB models start the simulation with a SOC level to 0.6. As before the first picture (see Figure 3-33) is related to the behaviour of the output power and of the reference power. One can immediately note that the two (the one of the static model and the one of the dynamic one output powers are identical but both differ from the reference one. This is due to the consumption of the auxiliaries (pumps and BMS) and to the efficiency of the PCS. The reference power is, in fact, used to control the battery output before the computation of the aux consumption and the PCS efficiency. The differences between the output power, the battery power and the aux power can be appreciated in Figure 3-34 (the values are in kW not in pu as in the previous graph).

![Figure 3-33. VRB Battery reference and output power; SOC.](image-url)
This inaccuracy of the model (also present in the ZEBRA’s) has no relevant impact because the external battery controller (explained in the next chapter), which has the task to set the reference values for the overall storage system, will be equipped with an integral controller that will avoid errors in steady state.

The SOC remains almost unchanged, the high ratio energy/power in the VRB is, in fact, the reason why such a short mission (2 hours length with charge and discharges) cannot reduce significantly the energy level in the storage. Figure 3-35 reports the cycle of SOC done (0.2 compared with 1.4 of the ZEBRA’s). A longer mission, performed in the next paragraph will be intended to test the two full size storage systems (i.e. the storage system ready to be coupled with the wind turbines).

Figure 3-36 reports the electrical parameters such as the OCV, the battery voltages and the currents. The differences between the two models are reduced to the initial step responses. Table 3-12 reports a results summary for the VRB models. As in the case of the ZEBRA, the VRB dynamic model presents an efficiency slightly higher, compared to the static one. Both however are around 80%.
3.3.2 Full configuration test

The two storage systems, ready to be coupled with the wind farm are here tested. Only the Dynamic model are going to be tested. The reference power is set by a PI controller sensible to the error between the reference power itself and the power produced by the battery. In this way the battery has to supply also the power required by the aux and compensate the losses of the PCS. The storage sizes are the one reported in Table 3-4:

- ZEBRA: 560 modules; nominal values 10 MW – 10 MWh; PCS size 4 MW
- VRB: 100 modules; nominal values 1.08 MW – 10 MWh; PCS size 1.5 MW

---

<table>
<thead>
<tr>
<th>Battery work (Wh)</th>
<th>Energy stored (Wh)</th>
<th>Energy released (Wh)</th>
<th>Joule losses (Wh)</th>
<th>Aux energy (Wh)</th>
<th>Efficiency w/o aux &amp; PCS</th>
<th>Efficiency w/o PCS</th>
<th>Efficiency ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRB Static</td>
<td>19431</td>
<td>9717</td>
<td>9714</td>
<td>2842</td>
<td>1337</td>
<td>87.2%</td>
<td>82.3%</td>
</tr>
<tr>
<td>VRB Dynamic</td>
<td>19429</td>
<td>9716</td>
<td>9713</td>
<td>2050</td>
<td>1339</td>
<td>90.5%</td>
<td>85.1%</td>
</tr>
</tbody>
</table>

Table 3-12. VRB mission summary result.
**ZEBRA**

Figure 3-37 reports the power diagrams. The reference power and the one limited are equivalent, due to the fact that no limitation temperature thresholds are triggered and regarding the fast/slow charge commutation the current is already below the minimum threshold (i.e. 0.5 pu). The battery power ($P_{battery}$) is higher (in discharge) than the output battery, which has the same value of the reference power commanded by the PI controller. The SOC protections are enabled when the minimum and the maximum allowed energy level are reached.

![Powers Diagram](image1)

![State Of Charge](image2)

Figure 3-37. ZEBRA powers; SOC.

Figure 3-38 show the variables of the electrochemical circuit. The OCV and the battery voltage are reported in the first diagram, it is remembered that the OCV for the Dynamic Model represent the voltage before the $R_0$ drop (thus including the RC chains voltage drops). The currents are reported in the second diagram: the battery current follows perfectly the reference controlled current.

Figure 3-39 at last reports the behaviour of the temperature. The initial temperature is 280 °C and increases steadily because the joule losses are greater than the thermal case losses. During the charge, with the increase of the SOC, the maximum allowed temperature goes down and thus the cooling fans are turned on.
A similar simulation is done for the VRB; however it is longer in order to allow a complete cycle of charge and discharge (remember that the energy/power nominal ratio is 2.5 h for the ZEBRA and 10 h for the VRB). The battery is stressed with a power request greater than its nominal value in order to analyze the thermal equivalent dynamic. The reference power, in fact, is 2 MW, while the maximum power that the battery can push in the PCS (i.e. the reference power limited) is 1.5 MW and finally the battery output (thus included the aux consumption, quite a lot for the VRB) is about 1.3 MW (see Figure 3-40).
It is interesting to note that, because the OCV is very dependant from the SOC (unlike the ZEBRA’s OCV), with the decrease of the SOC itself the current controller has to increase the current required (by lowering the battery voltage, reported in Figure 3-41).

The next graphs are helpful to describe the equivalent thermal dynamic of the VRB.

**Figure 3-40. VRB Powers; SOC.**

**Figure 3-41. VRB OCV and Battery voltages; Currents.**
The current is reported in the first diagram of Figure 3-42, while the square of the difference between the current and the reference value (1.2 pu in this case) is reported in second graph.

![Currents](image1)

![Delta I^2](image2)

**Figure 3-42. VRB Current and Delta I^2.**

The evaluation of the integral and the switch signal are reported in Figure 3-43.

![Di^2 Integral](image3)

![Switch](image4)

**Figure 3-43. VRB Delta I^2 integral and switch signal.**
Each 600 seconds the integral of the square of this delta is calculated. The result is a measured
in seconds because the current are in pu and if it is greater of 192 seconds a relay is triggered.
This value comes from the setting explained in the limitation paragraph (i.e. an extra 0.8 pu
current for 5 minutes each 10 minutes).
When the relays is triggered the reference current is limited to 1.2 for the rest of the time. At
the end of the 10th minute the integral counter is reset.

Results comparison

Table 3-13 reports a results summary for the two models. The comparison is intended to
evaluate the efficiency with the actual energy/power ratio. It can be seen that the high rated
power of the ZEBRA (10 MW) grants low Joule losses because the maximum power imposed by
the PCS is 4 MW. Moreover the ZEBRA has an extremely low aux energy requirements. This
lead to a an efficiency above 90%. Note that if left in stand by the ZEBRA battery would
consume about 15% of its nominal energy per day to balance the thermal losses (110 W per 24
h for the 17.8 kWh module).The VRB pays the low rated power with high Joule losses,
moreover the pumps require a good amount of energy thus the overall efficiency is about 80%.

<table>
<thead>
<tr>
<th></th>
<th>Battery work (Wh)</th>
<th>Energy stored (Wh)</th>
<th>Energy released (Wh)</th>
<th>Joule losses (Wh)</th>
<th>Aux energy (Wh)</th>
<th>Efficiency w/o aux &amp; PCS</th>
<th>Efficiency w/o PCS</th>
<th>Eff. ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEBRA</td>
<td>15,457,494</td>
<td>8,401,920</td>
<td>7,055,574</td>
<td>752,702</td>
<td>14,186</td>
<td>95.4%</td>
<td>95.3%</td>
<td>90.5%</td>
</tr>
<tr>
<td>VRB</td>
<td>15,664,631</td>
<td>9,593,702</td>
<td>6,071,228</td>
<td>1,954,882</td>
<td>999,669</td>
<td>88.9%</td>
<td>84.1%</td>
<td>79.9%</td>
</tr>
</tbody>
</table>

Table 3-13. ZEBRA and VRB full size mission summary result.

These two efficiencies are the one used to compute the roundtrip efficiencies (i.e. 0.9*0.9 for
the ZEBRA and 0.8*0.8 for the VRB), used in the economic evaluation.
4 SYSTEM CONTROL STRATEGIES

4.1 Layout

As foretold, the idea proposed in this thesis is to control the battery charging and discharging in order to control the whole plant power output at the Point of Common Coupling (PCC). An overview of the layout of the park is shown in Figure 4-1. The five 2 MW wind turbines are identified by the blocks on the right side of the picture while the battery (the ZEBRA in this case, otherwise the VRB) is located in the central block. The block that “calls” the wind speed profiles from the Matlab workspace is behind the picture of Eolo; while the measurements of the power transits and the power and energy references are included in the blocks just below Eolo’s one. The external battery and wind turbine controllers (or park controllers), that means the control blocks that create the reference power for the storage and the eventual reduction reference power for the wind turbines are in included in the greater block between Eolo’s one and the storage’s one [55].

The conceptual layout and the definitions of the powers can be observed in the Figure 4-2. The main inputs of the system are the five wind speeds, which are processed by the wind turbine models in order to compute the wind turbines production and thus the overall wind farm
output. The storage injects the power before the connection of the farm to the public grid, the power it has to release or to store is commanded by the external battery controller. The control logic inside the park controller block is the topic of the next paragraph. At last the algebraic sum of the storage output and of the wind farm output determines the PCC power.

![Figure 4-2. Park conceptual layout.](image)

### 4.2 Park controller

The external battery controller sets the reference power that the storage system has to accomplish, in order to perform the best strategy for the wind park and storage integrated system. Two controllers have been studied and implemented.

The first one, named *Power Control*, has the task to set the reference power to the storage in order to compensate the wind farm fluctuations and to have at the PCC the desired power profile. This kind of control is very rigid: if, in fact, a smooth power output is requested the control has to command a series of deep and very fast cycles of charge and discharge in order to compensate the fluctuation induced in the wind farm output by the turbulence. An excessive stress on the storage could be so realized and moreover an excess of energy depletion would result, due to the storage system losses, without taking a significant benefit to the system. If the main network is, in fact, very strong this kind of fluctuations could be easily absorbed by the power system, or at least being compensated by other wind farms output, located somewhere else.

A second control, named *Energy Control*, has thus been studied. This control differs from the previous one because it is more relaxed. The control action is realized within a longer time frame (i.e. 10 or 60 minutes instead of 1 second). As before, the desired power at the PCC is known, but it is not used in the control loop; it is used to compute the correspondent energy amount in the timeframe considered instead. This value is then equally divided in the time frame; it means that, for example, at half of the period the farm is expected to have produced half of the energy in the time frame considered. Thus the control loop uses the measure of the
cumulated energy produced by the wind farm each second and compares it with the expected energy. If the produced energy is the same (or it is inside a certain band, say ± 5%) no charge/discharge actions are performed, otherwise the more the distance from the objective value, the deeper the charge/discharge is required.

4.2.1 Power Control

The controller, shown in Figure 4-3, is equipped with a PI regulator and is sensible to the error between the power at the PCC (sum of the power produced by all the wind turbines and the one of the storage) and the expected reference power. The reference power could be the forecasted power each 10 minutes. Because it is beyond the scope of this thesis to evaluate the goodness of a wind power forecasting method, the reference power adopted in the simulations will simply be the mean power each 10 minutes. The power is calculated before the running of the simulations and is evaluated using the five 5-seconds sampled wind speeds and the static power curve of the wind turbine. Then the average power with a time period of 10 minutes of the overall output (i.e. the sum of the power output of the five wind turbines) is calculated and it is used as PCC reference power. The storage task will be to compensate instantaneously the wind farm fluctuations.

In order to avoid any blocking of the storage system due to maximum charge or minimum charge protection, it is present a feedback on the SOC [57], [58], [59], [60]. The reference PCC power is thus summed to another power signal generated by a Power-SOC characteristic. This feedback reduces or increases the battery reference power with the purpose to keep the SOC in an adequate range so that storage is always available (see Figure 4-3).

![Figure 4-3. Storage power controller scheme.](image)

The SOC feedback characteristic is reported in Figure 4-4. Whenever the SOC goes below 0.45 pu or above 0.75 pu the characteristic gives a signal that counteracts the reference park power. The threshold values can be changed depending on the kind of management that the battery is intended to perform. This restricted range of values forces the battery to remain inside a narrow SOC range and has been chosen just to show how the loop works.
4.2.2 **Energy Control**

The previous control strategy is very efficient if a perfectly smoothed power is requested. However, it could result in an excessive stress on the storage system, leading to premature aging and excessive power dissipation. The Power Control action can probably be realized in a much more efficient way by a flywheel or a supercapacitor or a storage system with an elevated power density (thus a reduced internal resistance) and a nominal high number of charge/discharge cycles (several thousand per year).

Moreover, it could not be necessary to have a perfectly smoothed output every second, but it could be enough to have the wind farm to produce the desired energy amount in a specific time frame (ten minutes for example). With this strategy, a useless number of charge/discharge actions, as well as a depletion of precious energy, can be avoided.

The control strategy described in [61] for the management of the loads is thus realized in Simulink and suited to the storage management. The energy reference value, calculated as before using the forecasted power production, is the energy that the farm is expected to produce each ten minutes. This value is then used to create the control energy function, that means the blue curve depicted in Figure 4-5.

![Figure 4-4. SOC feedback characteristic.](Image)

**Figure 4-4. SOC feedback characteristic.**

![Figure 4-5. Energy control strategies (parallel control band on the left; convergent one on the right).](Image)

**Figure 4-5. Energy control strategies (parallel control band on the left; convergent one on the right).**
This value, time dependant, is then compared with the cumulated energy produced by the farm. The control does not take any action if the two values are not coincident, but intervenes if the energy produced is above the red curve (the superior limit) or below the green one (the inferior limit). The two curves (the red and the green one) form the control band and with this shape (i.e. parallel curves), there is no warranty that at the end of the period (i.e. at the 600\textsuperscript{th} second) the energy produced will be equal to the reference value. This is due to the fact that this kind of control is a discrete-proportional type, thus a control action is taken if an error is generated but when the control variable is within the band (i.e. the control band) no corrective measurement are taken. If an integral action is intended to be realized the two control curves can be designed to be convergent at the end (or before) of the control period.

The realization in the Simulink block diagram is shown in Figure 4-6. The relays shown generate a signal (respectively negative for a charge command and positive for a discharge command) when the error (in per unit) is above 0. There is the problem however that when the relays trigger it commands a charge/discharge process at the maximum intensity.

An improvement can be done by adding more relays in parallel (i.e. four), each one triggered by a different threshold error. In this way for example if the error is above 0 but below 0.5\% a charge/discharge command for \(\frac{1}{4}\) of the maximum power is required, if it is not sufficient to take the control variable inside the band and thus the error increases above 0.5\% the second relays triggers and another \(\frac{1}{4}\) of power is commanded and so on. When the signal returns below a threshold the proper relays is reset.

Both power and energy controllers, however, are intended to set a battery management in the short period (within the day). The power and the energy reference values could be the result of a scheduling established the day ahead by means of an optimal management algorithm \cite{62} and \cite{63}. The main inputs for the optimization process would be the wind power forecast and
the expected hourly energy price, the algorithm output (i.e. the hourly energy reference values) are then intended to be tested in these Simulink models [64].

4.2.3 External Wind Turbine Controller

The external wind turbine controller, shown in Figure 4-7, forces the turbines to reduce their output, by means of a signal, generated by a PI controller sensible to the difference between the storage reference power and the actual output, which overrides the one generated by maximum power tracking curve. In fact, whenever there is the mandatory order from the DSO to grant zero power transit at the PCC and the battery is not able to store the whole energy produced by the turbines, in order to avoid the complete shutdown of the turbines, they can be forced to reduce their output. This situation can happen obviously if the storage is full, but also if it is not able to store all the power, because for example the PCS size is smaller compared to the wind farm output in that moment.

This controller is disabled during normal operational condition.

4.3 Simulations scenarios

The two storage systems, after being tested in standalone mode, are now coupled with the 10 MW wind farm. Their size is the one shown in Table 3-4 and here reported:

- ZEBRA: 560 modules; nominal values 10 MW – 10 MWh; PCS size 4 MW
- VRB: 100 modules; nominal values 1.08 MW – 10 MWh; PCS size 1.5 MW

The models version considered is the dynamic one (i.e. the one with the 3rd order electrochemical circuit) and not the static ones (i.e. the one with the first order circuit). The considered cases (done for both the storage technologies) are listed below:
In order to perform these simulations it is assumed that the forecasted power output of the park is correct, that means that every ten minutes a reference power, which depends on the mean wind speed, is sent to the plants. It is clear that at each time step the wind turbines will not produce the forecasted power because of the turbulence. The main task is hence to smooth the fast fluctuation induced in the wind by the local terrain roughness.

4.3.1 Scenario: Power Control

ZEBRA

Figure 4-8 reports the power produced by the 5 wind turbines (i.e. the wind farm output, red curve first diagram) and the output transit at the PCC (blue curve), smoothed by the ZEBRA’s work. The second diagram reports the reference power (i.e. the forecasted wind turbine outputs ten minutes averaged, that means without turbulence) and the reference power modified by the SOC feedback. In this scenario the SOC feedback is not enabled thus the two curves coincide.
The resulting battery power output is reported in Figure 4-9 along with the SOC behaviour. It can be seen how the SOC keeps decreasing due to the fact that the storage has some losses and the power compensation is zero mean value.

Without any action the storage would be unavailable in some hours due to the minimum SOC protection. Another significant graph is the temperature’s one reported in Figure 4-10. Because the power output of the storage is not very intense (the nominal power of the ZEBRA is 10 MW, limited to 4 MW because of the PCS size and the maximum power required is about 2 MW) the Joule losses are not sufficient to compensate the case thermal losses and thus, due to negative thermal energy balance, the temperature decreases. At 260 °C the heater is turned on to reheat the battery.
**VRB**

As for the ZEBRA, Figure 4-11 offers the behaviour of the power transits for the VRB system. Figure 4-12 reports the storage output and SOC.

---

**Figure 4-11.** VRB PCC and farm power; Reference power.

**Figure 4-12.** VRB Battery power; SOC.
The battery power is below 1.5 MW due to the PCS size limit. The SOC in this case goes down faster than before because of the increased internal losses of the VRB compared to the ZEBRA.

Results comparison

The main results regarding the power and energy measurement of the two simulations are reported in Table 4-1 and Table 4-2. The first table summarizes the energy transited at the PCC and in/out the battery and the one produced by the Farm in the 12 hours period analyzed. For comparison the reference energies (i.e. the expected farm production) are reported, the first one called Mod Ref Energy is the energy calculated from the reference power modified by the SOC feedback, while the other is the original reference. In this case the two references coincide because the SOC feedback is disabled.

The Mean Ref Power is simply the mean of the Ref Energy in the 12 hours considered. The last two values, the deviations (or power turbulence), are the same indicators used in the wind turbine simulations scenario to evaluate the degree of variation of the power in 10-minutes windows. The smoothing actions of the storages prove to be effective because of the reduction of the power turbulence degree from 11.8% to 2.1% for the ZEBRA and to 1.8% for the VRB. In this scenario the current control loop speed (mainly identified by the parameters of the PI regulator and by the voltage delay) has an important role in the determination of the smoothing efficiency. Because no specific information are available the same values have been adopted and thus the results are very similar. Though, the slight difference (1.8% vs 2.1%) could reside in the different electrochemical circuit time constant: both the short time constants value 6 seconds, while the long time constant for the VRB is 60 seconds versus the 600 seconds of the ZEBRA, thus proving the VRB to be faster respondent.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC Energy (MWh)</td>
<td>65.165</td>
<td>65.130</td>
</tr>
<tr>
<td>Farm Energy (MWh)</td>
<td>64.076</td>
<td>64.076</td>
</tr>
<tr>
<td>Mod Ref Energy (MWh)</td>
<td>65.191</td>
<td>65.191</td>
</tr>
<tr>
<td>Ref Energy (MWh)</td>
<td>65.191</td>
<td>65.191</td>
</tr>
<tr>
<td>Mean Ref Power (MW)</td>
<td>5.433</td>
<td>5.433</td>
</tr>
<tr>
<td>Farm Mean Power Dev (%)</td>
<td>11.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>PCC Mean Power Dev (%)</td>
<td>2.1%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Table 4-1. Power Control system results.

Table 4-2 reports the results concerning the battery. It shows the maximum PCS power, the stored and the released energy and their sum: the battery work (i.e. the sum of stored and released energies, both considered positive). The stored and the released energy are the integrals respectively of the negative and the positive $P_{battery}$. It is worth noting that $P_{battery}$ is
the power at the battery connection point thus not considering the aux contribution and the PCS efficiency (see Figure 3-26).

The Joule and the aux energies as well as the efficiencies are also listed. The PCS load factor gives an idea of the power ratio used compared to the PCS nominal power (4 MW for the ZEBRA, 1.5 for the VRB). In the ZEBRA, for example, the mean power is just the 13% of the PCS power (i.e. 520 kW), thus meaning that it could result oversized for the task studied. The VRB presents a 31% load factor (i.e. 465 kW) instead. This aspect is also the justification for the higher efficiency value achieved by the ZEBRA. The low load factor, in fact, implies lower per unit current and thus lower joule losses. The last values are the number of SOC cycles, i.e. the ratio between the battery work and the nominal energy (10 MWh).

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power (MW)</td>
<td>4.000</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery work (MWh)</td>
<td>5.562</td>
<td>5.553</td>
</tr>
<tr>
<td>Stored Energy (MWh)</td>
<td>1.960</td>
<td>1.918</td>
</tr>
<tr>
<td>Released Energy (MWh)</td>
<td>3.602</td>
<td>3.634</td>
</tr>
<tr>
<td>Joule Energy (MWh)</td>
<td>0.056</td>
<td>0.477</td>
</tr>
<tr>
<td>Aux Energy (MWh)</td>
<td>0.269</td>
<td>0.378</td>
</tr>
<tr>
<td>Efficiency w/o aux &amp; PCS</td>
<td>99.0%</td>
<td>92.1%</td>
</tr>
<tr>
<td>Efficiency w/o PCS</td>
<td>94.5%</td>
<td>86.7%</td>
</tr>
<tr>
<td>Efficiency ultimate</td>
<td>89.8%</td>
<td>82.3%</td>
</tr>
<tr>
<td>PCS load factor (pu)</td>
<td>0.13</td>
<td>0.31</td>
</tr>
<tr>
<td>Number of SOC cycles</td>
<td>0.56</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 4-2. Power Control battery results.

4.3.2 **Scenario: Power Control with SOC feedback**

The same scenario is studied with the SOC feedback enabled. The SOC characteristic is the one shown in Figure 4-4: whenever the SOC is below 0.45 a charge signal is generated. The reference power is thus “corrected” by this SOC feedback signal, the more the SOC is low the greater is the feedback intensity.

**ZEBRA**

The SOC feedback begins its action after the 11th hour, as depicted in the second diagram of Figure 4-13. The Reference Mod Power value and the original one differ. The SOC, in fact, is kept above 0.45 as can be seen in the second diagram of Figure 4-14. Despite of this feedback, the smoothing action is still effective.
Figure 4-13. ZEBRA PCC and farm power; Reference power.

Figure 4-14. ZEBRA Battery power; SOC.

**VRB**

Figure 4-15 and Figure 4-16 report the results in the case of the VRB. This time the feedback compensation starts before (around the 6th hour).
Results comparison

The simulation results are reported in Table 4-3 and in Table 4-4. The differences can be firstly noted in the PCC energy: the batteries release less energy. The Ref Energies and the Mod Ref
Energies are different. Despite of the SOC feedback, the PCC Mean Power Deviations remain unchanged, that means that the smoothing action is still effective.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC Energy (MWh)</td>
<td>64.999</td>
<td>64.339</td>
</tr>
<tr>
<td>Farm Energy (MWh)</td>
<td>64.076</td>
<td>64.076</td>
</tr>
<tr>
<td>Mod Ref Energy (MWh)</td>
<td>64.999</td>
<td>64.383</td>
</tr>
<tr>
<td>Ref Energy (MWh)</td>
<td>65.191</td>
<td>65.191</td>
</tr>
<tr>
<td>Mean Ref Power (MW)</td>
<td>5.417</td>
<td>5.365</td>
</tr>
<tr>
<td>Farm Mean Power Dev (%)</td>
<td>11.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>PCC Mean Power Dev (%)</td>
<td>2.0%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Table 4-3. Power Control with SOC feedback system results.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power (MW)</td>
<td>4.000</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery work (MWh)</td>
<td>5.552</td>
<td>5.490</td>
</tr>
<tr>
<td>Stored Energy (MWh)</td>
<td>2.037</td>
<td>2.290</td>
</tr>
<tr>
<td>Released Energy (MWh)</td>
<td>3.514</td>
<td>3.201</td>
</tr>
<tr>
<td>Joule Energy (MWh)</td>
<td>0.055</td>
<td>0.422</td>
</tr>
<tr>
<td>Aux Energy (MWh)</td>
<td>0.270</td>
<td>0.367</td>
</tr>
<tr>
<td>Efficiency w/o aux &amp; PCS</td>
<td>99.0%</td>
<td>92.9%</td>
</tr>
<tr>
<td>Efficiency w/o PCS</td>
<td>94.5%</td>
<td>87.4%</td>
</tr>
<tr>
<td>Efficiency ultimate</td>
<td>89.7%</td>
<td>83.1%</td>
</tr>
<tr>
<td>PCS load factor (pu)</td>
<td>0.13</td>
<td>0.30</td>
</tr>
<tr>
<td>Number of SOC cycles</td>
<td>0.56</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 4-4. Power Control with SOC feedback battery results.

Next pictures report a comparison between the two storage results. The first graph of Figure 4-17 shows the 10-minutes reference average power and the ones at the PCC in the case of ZEBRA and of VRB. The respective SOC behaviour are reported subsequently.

Figure 4-18 reports the 10-minutes standard deviations (in pu, thus divided by the correspondent 10-minutes average power). It can be noted how the deviation is most of the time minor than 0.02 pu compared to the deviation of the five turbines production which ranges from 0.05 to 0.30 pu.
Figure 4-17. 10-minutes ZEBRA&VRB PCC and farm power comparison; SOC.

Figure 4-18. 10-minutes standard deviation in pu (reported on the average mean power).

4.3.3 Scenario: Energy Control

In this scenario the energy control strategy is tested.
ZEdra

The PCC power transit and the farm power are reported in Figure 4-19. By the comparison with Figure 4-8 it can be easily seen that both the powers (the one produced by the wind farm and the one at the PCC that includes the contribution of the storage) are very variable. This is due to the fact that the storage is not asked to smooth the power output but to grant, at the end of each 10th minutes, that the energy produced is equivalent to the forecasted (with a tolerance of ±1%).

In the storage power diagram (see Figure 4-20), it can be appreciated how the controller commands the battery. The power output is, in fact, characterized by a series of power steps of 1 MW. The more the distance from the target energy at the end of the controlling window the higher the reference power set by the controller (in this case a 4 four steps logic with 1 MW per step has been chosen).

In this way the storage’s burden is minor compared with the previous control strategy. As foretold the previous control strategy is probably much more indicated for a fast-respondent device such as a flywheel.

Figure 4-19. ZEBRA PCC and farm power; Reference power.
Figure 4-20. ZEBRA battery power; SOC.

Figure 4-21 shows, in the first diagram, the energy control signal (in blue), the thresholds (the upper in red and the lower in green) and the measured energy (in black). The difference between the measured energy and the reference one is reported in the second diagram (in pu, thus divided by the reference energy). This error is always below 1%.

Figure 4-21. ZEBRA energy; Energy error.
A detail of the previous graph is reported in Figure 4-22 where a single controlling-window (600 seconds) is shown. Whenever the measured energy overcomes a threshold the control command a charge (or discharge) action to the storage in order to have the PCC energy produced within the boundaries. The greater is the error and the wider is the command intensity.

![Energy and Battery Power Graphs](image)

**Figure 4-22. ZEBRA Energy detail; Battery reference power detail.**

**VRB**

The same analysis is performed also for the VRB system. The powers are reported in Figure 4-23 and in Figure 4-24. The maximum power that the storage is allowed to manage is, for the VRB, around 1.5 MW. Thus the four power steps of the control system, that were equal to 1 MW in the case of the ZEBRA, are now equal to 0.4 MW.
It is, however, interesting to pose the attention on the second graph of Figure 4-25, where the relative error between the measured and the desired energy is shown. The error is, in some time frame, greater than 1%. This means that the VRB power could result not sufficient to compensate the energy error. It has to be considered, in fact, that with this control strategy,
the battery is forced to do most of the work in the final part of the time-frame (see Figure 4-26) and if the power is not enough, the energy released (or stored) could not be sufficient to take the PCC energy to the desired value.

![Figure 4-25. VRB energy; Energy error.](image1)

![Figure 4-26. VRB Energy detail; Battery reference power detail.](image2)
**Results comparison**

The comparison of the results for this scenario are shown in Table 4-5 and in Table 4-6. It can be noted that no smoothing effect on the power transit at the PCC is achieved (look also at Figure 4-27). Indeed, the power quality (defined as the variability of the power transit compared to a reference value) gets worse.

Concerning the battery results, it is worth noting that the ZEBRA efficiency is reduced compared to the previous case due to the less usage. The ratio between overall losses and useful work is higher.

The number of SOC cycles is considerably reduced too, passing from 0.55 to respectively (ZEBRA and VRB) 0.18 and 0.13.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC Energy (MWh)</td>
<td>65.052</td>
<td>64.829</td>
</tr>
<tr>
<td>Farm Energy (MWh)</td>
<td>64.076</td>
<td>64.076</td>
</tr>
<tr>
<td>Mod Ref Energy (MWh)</td>
<td>65.191</td>
<td>65.191</td>
</tr>
<tr>
<td>Ref Energy (MWh)</td>
<td>65.191</td>
<td>65.191</td>
</tr>
<tr>
<td>Mean Ref Power (MW)</td>
<td>5.433</td>
<td>5.433</td>
</tr>
<tr>
<td>Farm Mean Power Dev (%)</td>
<td>11.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>PCC Mean Power Dev (%)</td>
<td>12.7%</td>
<td>12.0%</td>
</tr>
</tbody>
</table>

**Table 4-5.** Energy Control system results.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power (MW)</td>
<td>4.000</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery work (MWh)</td>
<td>1.763</td>
<td>1.292</td>
</tr>
<tr>
<td>Stored Energy (MWh)</td>
<td>0.250</td>
<td>0.197</td>
</tr>
<tr>
<td>Released Energy (MWh)</td>
<td>1.550</td>
<td>1.098</td>
</tr>
<tr>
<td>Joule Energy (MWh)</td>
<td>0.032</td>
<td>0.161</td>
</tr>
<tr>
<td>Aux Energy (MWh)</td>
<td>0.272</td>
<td>0.087</td>
</tr>
<tr>
<td>Efficiency w/o aux &amp; PCS</td>
<td>98.2%</td>
<td>88.9%</td>
</tr>
<tr>
<td>Efficiency w/o PCS</td>
<td>85.3%</td>
<td>83.9%</td>
</tr>
<tr>
<td>Efficiency ultimate</td>
<td>81.0%</td>
<td>79.7%</td>
</tr>
<tr>
<td>PCS load factor (pu)</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Number of SOC cycles</td>
<td>0.18</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**Table 4-6.** Energy Control battery results.
4.3.4 Scenario: Energy Control with wrong forecast

ZEBRA

In order to properly test the goodness of the Energy Control, the wind profiles are fictitiously changed. The odd hour profiles (the 1\textsuperscript{st}, the 3\textsuperscript{rd}, etc...) are changed by -1 m/s wind speed, while the even hours (the 2\textsuperscript{nd}, the 4\textsuperscript{th}, etc...) see an increment of 1 m/s. The reference power and energy are of course unchanged.

The differences in the wind farm power production can be immediately noted in the first graph of Figure 4-28, while the reference power (second graph) is the same seen in the previous scenarios. It is worth noting how a slight variation of the wind speed of just 1 m/s implies (especially when the wind is blowing between 7 and 11 m/s, see Figure 1-1) a noticeable power output variation.

The storage system has thus to perform a consistent compensation because of the deviation from the produced energy and the forecasted one. The charge and discharge patterns can be appreciated in the first graph of Figure 4-29, while the second one reports the behaviour of the SOC, which is overall going down.
The greater usage of the storage increases the Joule losses and thus the thermal balance (i.e. the difference between the lost thermal power through the case and the internal heat) is close to zero, nevertheless still negative. Thus the temperature, in Figure 4-30, keeps on decreasing, even if slowly than before.
In the energy graphs of Figure 4-31, it can be seen that the ZEBRA system is capable to compensate the error successfully, even if, at the end of the 12th hour the minimum SOC protection prevents the storage from performing further discharges. The energy error gets above the 4%.

The control action can be now clearly appreciated in Figure 4-32: the energy measured (black curve) is minor than the one forecasted and when it overcomes the inferior limit (green curve) a discharge command is set. The amplitude of this command grows if the sum of the wind farm energy plus the released storage energy is not sufficient to take the PCC energy (i.e. the measured energy) within the desired boundaries.
The VRB correspondent scenario is here reported. As always the PCC, farm and reference powers are firstly reported (see Figure 4-33), along with the battery output (see Figure 4-34).

**Figure 4-32. ZEBRA Energy detail; Battery reference power detail.**

**VRB**

**Figure 4-33. VRB PCC and farm power; Reference power.**
It is very interesting to pay attention to the energy graph and, especially, to the energy error in the second diagram of Figure 4-35. The relative error is sometimes more than 10%. The reason, as in the previous case, can be searched in the low power ratio of the storage system compared to the size of the wind farm (1.5 MW vs 10 MW of the wind farm).

![Figure 4-34. VRB battery power; SOC.](image1)

![Figure 4-35. VRB energy; Energy error.](image2)
Results comparison

In the result Table 4-7 it can be seen that both the configuration are not able to grant the desired amount of energy at the PCC. The ZEBRA’s system however is able to take its PCC energy nearer to the reference value than the VRB’s system. The power quality, intended as always as the variability of the power transit at the PCC, has got worst for both the systems compared to the farm power variability.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC Energy (MWh)</td>
<td>64.971</td>
<td>62.644</td>
</tr>
<tr>
<td>Farm Energy (MWh)</td>
<td>63.832</td>
<td>63.832</td>
</tr>
<tr>
<td>Mod Ref Energy (MWh)</td>
<td>65.192</td>
<td>65.192</td>
</tr>
<tr>
<td>Ref Energy (MWh)</td>
<td>65.192</td>
<td>65.192</td>
</tr>
<tr>
<td>Mean Ref Power (MW)</td>
<td>5.433</td>
<td>5.433</td>
</tr>
<tr>
<td>Farm Mean Power Dev (%)</td>
<td>11.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>PCC Mean Power Dev (%)</td>
<td>18.6%</td>
<td>14.6%</td>
</tr>
</tbody>
</table>

Table 4-7. Energy Control with wrong forecast system results.

The battery results of Table 4-8 highlight an higher use of the storage systems with a number of SOC cycles equal to 1.38 for the ZEBRA and 0.92 for the VRB.
4.3.5 *Scenario: Zero transit at the PCC*

This last scenario envisages the possibility to set to zero the power transit at the PCC for a certain period (30 minutes in this case). The task of the battery is thus to store all the amount of energy produced by the farm. However, if the storage is unable to completely fulfil the duty the external wind turbine controller has to command a reduction of the wind turbine outputs in order to have zero transit at the PCC (note that it is not an islanding).

The external battery controller activated is the Power Control because an instantaneous control of the power transit is required and the Energy Control would not be able to grant it.

**ZEBRA**

The first picture reported is always the one referred to the power transits and references. It can be seen that from the first minute the reference power starts decreasing. The slope is bound to the 20% of the farm nominal power per minute (thus 2 MW/min). The PCC power gets to zero within few seconds after the reference power value got to zero, as depicted in Figure 4-37. The storage system is thus able to take all the power coming from the farm, that for the timeframe considered does not go above 4 MW.

The ZEBRA power, reported in Figure 4-38, is, in fact, almost equal to the farm production. The SOC increases from 0.6 to about 0.8, that means that 2 MWh were stored in the 30 minutes window.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power (MW)</td>
<td>4.000</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery work (MWh)</td>
<td>13.833</td>
<td>9.198</td>
</tr>
<tr>
<td>Stored Energy (MWh)</td>
<td>5.978</td>
<td>4.604</td>
</tr>
<tr>
<td>Released Energy (MWh)</td>
<td>7.855</td>
<td>4.594</td>
</tr>
<tr>
<td>Joule Energy (MWh)</td>
<td>0.384</td>
<td>1.724</td>
</tr>
<tr>
<td>Aux Energy (MWh)</td>
<td>0.027</td>
<td>0.704</td>
</tr>
<tr>
<td>Efficiency w/o aux &amp; PCS</td>
<td>97.3%</td>
<td>84.2%</td>
</tr>
<tr>
<td>Efficiency w/o PCS</td>
<td>97.1%</td>
<td>79.1%</td>
</tr>
<tr>
<td>Efficiency ultimate</td>
<td>92.3%</td>
<td>75.2%</td>
</tr>
<tr>
<td>PCS load factor (pu)</td>
<td>0.30</td>
<td>0.51</td>
</tr>
<tr>
<td>Number of SOC cycles</td>
<td>1.38</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Table 4-8. Energy Control with wrong forecast battery results.
The ZEBRA temperature (see Figure 4-39) is quite unchanged in the overall hour. That means that the Joule losses and the case thermal losses are almost balanced.
VRB

The same scenario is proposed for the VRB system and in this case it can be immediately noticed that the reduced PCS size (1.5 MW) is of course not able to store all the 4 MW produced by the farm.

Figure 4-40 shows, in fact, that the PCC power transit gets to zero, but the farm production result shed. This is due to the intervention of the External turbine controller that has reduced the turbine’s outputs.

The VRB power is equal to 1.5 MW (plus the consumption of the aux and the PCS losses) as shown in Figure 4-41.
How the turbine power reduction signals has effect on the turbines can be appreciated in the following pictures. Figure 4-42 reports the wind speed and the pitch angle, along with the MPT reference power and the effective output power.

Figure 4-41. VRB battery power; SOC.

Figure 4-42. Windspeed and Pitch; MPT and Output power; Rotational speed.
The external power signal is added to the MPT signal (see Figure 2-18) and try to reduce the generator electrical torque on the shaft in order to reduce the power output. This causes an acceleration of the shaft due to the unbalance between the accelerating torque (induced by the wind) and the braking torque (the electrical one). When the rotational speed goes above 1 pu the pitch control system increases the pitch angle of the blades in order to reduce the power coefficient (shown in Figure 4-43) and thus the accelerating torque. Because the shaft has sped up, the MPT control system would command a greater MPT reference power to counteract the acceleration. However the external signal, that comes from an integral type controller (the External turbine controller), keeps on forcing a negative signal power in order to have the overall turbine set to produce just the power that the storage system is able to take.

![Tip Speed Ratio and Pitch Angle](image1)

![Power Coefficient](image2)

Figure 4-43. Tip Speed Ratio and Pitch; Power coefficient.

**Results comparison**

At last the system results are shown in Table 4-9. Both the configurations achieve the desired result (the reference power and the PCC energy are almost equal). Of course in the case of the VRB, it has been required to shed some farm production. Table 4-10 reports the battery information. What is immediately noticeable is the PCS load factor that in the case of the VRB has almost been equal to 1.
Table 4-9. Zero Transit at the PCC system results.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC Energy (MWh)</td>
<td>1.939</td>
<td>1.961</td>
</tr>
<tr>
<td>Farm Energy (MWh)</td>
<td>3.593</td>
<td>2.772</td>
</tr>
<tr>
<td>Mod Ref Energy (MWh)</td>
<td>1.919</td>
<td>1.919</td>
</tr>
</tbody>
</table>

Table 4-10. Zero Transit at the PCC battery results.

<table>
<thead>
<tr>
<th></th>
<th>ZEBRA (4MW – 10 MWh)</th>
<th>VRB (1.08 MW – 10 MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power (MW)</td>
<td>4.000</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery work (MWh)</td>
<td>1.881</td>
<td>1.047</td>
</tr>
<tr>
<td>Stored Energy (MWh)</td>
<td>1.717</td>
<td>0.874</td>
</tr>
<tr>
<td>Released Energy (MWh)</td>
<td>0.164</td>
<td>0.173</td>
</tr>
<tr>
<td>Joule Energy (MWh)</td>
<td>0.056</td>
<td>0.088</td>
</tr>
<tr>
<td>Aux Energy (MWh)</td>
<td>0.002</td>
<td>0.055</td>
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<tr>
<td>Efficiency w/o aux &amp; PCS</td>
<td>97.1%</td>
<td>92.2%</td>
</tr>
<tr>
<td>Efficiency w/o PCS</td>
<td>97.0%</td>
<td>87.9%</td>
</tr>
<tr>
<td>Efficiency ultimate</td>
<td>92.1%</td>
<td>83.5%</td>
</tr>
<tr>
<td>PCS load factor (pu)</td>
<td>0.19</td>
<td>0.97</td>
</tr>
<tr>
<td>Number of SOC cycles</td>
<td>0.19</td>
<td>0.10</td>
</tr>
</tbody>
</table>
5 CONCLUSIONS

5.1 Considerations about the work done

The present thesis focused on the development of models of wind turbines and storage systems, in Matlab-Simulink environment, useful for implementing integrated control strategies of the whole resulting system in order to describe the benefits that storage can provide to renewable generation. The main purpose was the facilitation of the integration of distributed, intrinsically not dispatchable, generation in the electric grid.

A deep characterization of the wind profiles has been performed. The 2 MW turbine model was described from an electromechanical perspective, thus the work has provided: an analysis of the aerodynamic behaviour of the rotor including the pitch control system, the shaft dynamic and the maximum power tracking characteristic. The stand alone model and the complete wind farm, composed by 5 machines with different wind speeds, have been studied.

The two storage systems, a flow battery (VRB) and a high temperature battery (ZEBRA) have been fully characterized from both the electrochemical and the thermal perspective, included all the limitations and the protections systems. All the dynamics were built in the equivalent cell and the desired sizes of the storage systems (1.08 MW - 10 MWh for the VRB and 4 MW – 10 MWh for the ZEBRA) were obtained by multiplying the cell parameters for the number of series/parallel elements.

The storage model has been realized and described in order to have a general validity, even if for these study purposes has been tailored for two specific chemistries. For each technologies two dynamic models, named Static and Dynamic, have been developed. The Static one provided a description of the electrochemical circuit with no characterization of the delays introduced by the chemical reactions. The Dynamic one included a third order circuit with two delays instead. The models have been tested by means of charge/discharge cycles at different intensity and the comparison between the different models have been done.

Two control strategies have been envisaged, the first one named Power Control and the second one Energy Control, with the aim of setting the battery charging and discharging phases in order to control the whole plant output. Afterward each battery model has been coupled with the wind farm and several scenarios were analyzed: the first one regarded the possibility to smooth the wind park turbulent output by the charge/discharge control of the battery; the second one analyzed the implementation of the generation shifting; the third one analyzed the possibility to control the storage to collect the power produced by the wind
turbine in case of order by the DSO to reduce or to have zero power output at PCC and proved the possibility to reduce the wind farm output, without any turbine disconnection, in case of need.

It was thus highlighted how the storage system could grant benefits in term of controllability of the wind park output. However, the rigid Power Control, whose aim was to pursue a perfectly smoothed output, proved to be very stressful for the storage, threatening the battery lifetime. Nevertheless this control has proved good performance in the zero transit scenario. The Energy Control allowed a more smart management of the storage, granting the desired energy production at the PCC, without, however, any particular regard to the smoothness of the overall generated power profile.

5.2 Future developments

This thesis was intended as a guide for further validation studies on real test facilities. The next studies, in fact, will regard the validation of the battery model, in order to insert proper values for the time constants and will envisage other control strategies. Further analysis of the two control strategies and variations such as considering different control windows as well as different control band patterns will be envisaged.

These dynamic storage models are currently used as a benchmark to realize a discrete-time model to perform optimal management studies in Matlab environment, in response to price signal that may be available from the electricity market.

The ZEBRA model is intended to be translated and used in DlgSILENT PowerFactory simulation environment in order to perform dynamic studies also concerning the impact of the electric cars in the distribution network.

A validation of the VRB model is expected to be performed during the current Spring in the test facility of the Risø in Roskilde, Denmark.

Further validations of both the storage models are expected to be done later in the current year in the test facility of ENEL in Livorno, Italy.
Chapter 1


Chapter 2


[27] Wind Speed Data from Valledolmo Wind Farm (Palermo, Italy), ENEL, 2009.


Chapter 3

[41] Cebi (ZEBRA manufacturer) website: http://www.cebi.com/
[49] E. Micolano, M. Broglia, L. Mazzocchi and C. Bossi, “Sviluppo di modelli di sistemi di accumulo di tipo tradizionale ed avanzato per impieghi nella generazione distribuita al fine della loro rappresentazione in sistemi complessi (Traditional and advanced storage system models development for embedded generation uses in complex systems...
Chapter 4


LIST OF PUBLICATIONS DURING THE PHD

Conference and Workshop Proceedings


Journal, Transaction, Book publications


Master Degree Thesis (co-supervisor)


## APPENDIX

### Battery Data Summary Table

<table>
<thead>
<tr>
<th>Dynamic</th>
<th>Parameters</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage (V)</td>
<td>2.58</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Current (A)</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Capacity (Ah)</td>
<td>32</td>
<td>Independent</td>
</tr>
<tr>
<td></td>
<td>Power (W)</td>
<td>82.6</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>Energy (Wh)</td>
<td>82.6</td>
<td>Independent</td>
</tr>
<tr>
<td></td>
<td>Max current in charge-discharge (A) / (pu)</td>
<td>62 A / 2 pu</td>
<td>80 A / 2 pu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>96 A / 3 pu</td>
<td></td>
</tr>
</tbody>
</table>

### CELL nominal data

<table>
<thead>
<tr>
<th>Cell Configuration (#S - #P)</th>
<th>108 S ÷ 2 P</th>
<th>40 S ÷ (2+2+1) P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>278.6</td>
<td>54</td>
</tr>
<tr>
<td>Current (A)</td>
<td>64</td>
<td>200 (80+80+40)</td>
</tr>
<tr>
<td>Capacity (Ah)</td>
<td>64</td>
<td>1850</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>17.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Maximum Power (kW) / (pu)</td>
<td>30 kW / 1.7 pu</td>
<td>15 kW / 1.4 pu</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>17.8</td>
<td>100</td>
</tr>
<tr>
<td>Usable energy (kWh)</td>
<td>14.2</td>
<td>80</td>
</tr>
<tr>
<td>SOC range (pu)</td>
<td>0.2 ÷ 1 (80%)</td>
<td>0.2 ÷ 1 (80%)</td>
</tr>
</tbody>
</table>

### BATTERY nominal data

#### Open Circuit Voltage: OCV (V)

<table>
<thead>
<tr>
<th>OCV Range: Cell / Battery (V)</th>
<th>2.33 (@SOC 0.2) ÷ 2.65 (@SOC 1) / 252 ÷ 286</th>
<th>1.28 (@SOC 0.2) ÷ 1.6 (@SOC 1) / 51.2 ÷ 64.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCV Range (pu)</td>
<td>0.90 ÷ 1.03</td>
<td>0.92 ÷ 1.14</td>
</tr>
</tbody>
</table>

#### Total Internal Resistance (mΩ)

<table>
<thead>
<tr>
<th>Total Internal Resistance (mΩ)</th>
<th>SOC dependant (see Look-up table)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Res. (= V_{nom}/I_{nom})</td>
<td>R_{cell} / R_{battery} (mΩ)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80.6 / 4353</td>
</tr>
</tbody>
</table>

#### Resistance Range and Average: Cell / Battery (mΩ)

<table>
<thead>
<tr>
<th>Resistance Range and Average: Cell / Battery (mΩ)</th>
<th>SOC &amp; T dependant (see Look-up tables)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9% ÷ 33% – Ave= 19%</td>
</tr>
</tbody>
</table>

### Electrochemical equivalent (Cell/Battery Parameters)

#### Open Circuit Voltage: OCV (V)

<table>
<thead>
<tr>
<th>OCV Range: Cell / Battery (V)</th>
<th>2.33 (@SOC 0.2) ÷ 2.65 (@SOC 1) / 252 ÷ 286</th>
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#### Total Internal Resistance (mΩ)

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<tr>
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<th>SOC dependant (see Look-up table)</th>
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<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Res. (= V_{nom}/I_{nom})</td>
<td>R_{cell} / R_{battery} (mΩ)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80.6 / 4353</td>
</tr>
</tbody>
</table>

#### Resistance Range and Average: Cell / Battery (mΩ)

<table>
<thead>
<tr>
<th>Resistance Range and Average: Cell / Battery (mΩ)</th>
<th>SOC &amp; T dependant (see Look-up tables)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9% ÷ 33% – Ave= 19%</td>
</tr>
</tbody>
</table>
### Dynamic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_2$ (mΩ) (short)</td>
<td>1.9 (constant)</td>
<td>1.9 (constant)</td>
</tr>
<tr>
<td>$T_1$ (s) (long time constant)</td>
<td>600</td>
<td>60</td>
</tr>
<tr>
<td>$T_2$ (s) (short time constant)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$C_1$ = $T_1 / R_1$ (F)</td>
<td>600 / $R_1$</td>
<td>60 / $R_1$</td>
</tr>
<tr>
<td>$C_2$ = $T_2 / R_2$ (F)</td>
<td>3158</td>
<td>6 / $R_2$</td>
</tr>
<tr>
<td>Shunt Losses</td>
<td>None</td>
<td>3% $I_{dc}$ (if working)</td>
</tr>
</tbody>
</table>

### Current Control Loop (Cell/Battery Parameters)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Controller: $kp \div Ti$ (pu ÷ s)</td>
<td>5 ÷ 0.1</td>
<td>5 ÷ 0.1</td>
</tr>
<tr>
<td>Min ÷ Max Voltages allowed:</td>
<td>1.7 ÷ 3.1 / 184 ÷ 335</td>
<td>1.0 ÷ 1.7 / 40 ÷ 68</td>
</tr>
<tr>
<td>Cell / Battery (V)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min ÷ Max Voltage (pu)</td>
<td>0.66 ÷ 1.20</td>
<td>0.74 ÷ 1.26</td>
</tr>
<tr>
<td>Voltage Time Delay (s)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Voltage Rate Limit (pu/s)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Protections

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Charge (SOC)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Minimum Charge (SOC)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Minimum Temperature &amp; Minimum SOC</td>
<td>Charge requested if: SOC &lt; SOC_{min} &amp; T &lt; T_{min} (energy needed for heater)</td>
<td>None</td>
</tr>
</tbody>
</table>

### Limitations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Charge: CC-CV (SOC)</td>
<td>@ 0.8 SOC: charge power reduced from 2 pu to 0.5 pu</td>
<td>None</td>
</tr>
<tr>
<td>Maximum Temp. In Charge</td>
<td>SOC dependant: charge intensity reduced from 2 pu to 0.5 pu</td>
<td>Overload capability based on the cell thermal inertia (based on energy balance): max current 2 pu for 5 minutes each 10 minutes</td>
</tr>
<tr>
<td>Maximum Temp. In Discharge</td>
<td>@ 340 °C: discharge power reduced from 3 pu to 1 pu</td>
<td></td>
</tr>
</tbody>
</table>

### Thermal Dynamic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</th>
<th>Vanadium – Redox (VRB: FB10 - 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Thermal Losses ($W_{in}$)</td>
<td>110 W ($T_{cell} = 300 °C &amp; T_{env} = 25°C$)</td>
<td></td>
</tr>
<tr>
<td>Case Thermal Time Constant</td>
<td>168 h (= 604800 s) (time needed to get from 300°C to 25 °C ±5% if shut down)</td>
<td>Cell thermal parameters unknown: Overload capability based on the equivalent thermal inertia</td>
</tr>
<tr>
<td>Case Thermal Resistance $R_{th}$ (K/W)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Battery Thermal Capacitance $C_{th}$ (J/K) ($C_{th} = 3* T/ 3*R_{th}$)</td>
<td>80640</td>
<td></td>
</tr>
<tr>
<td>Dynamic Parameters</td>
<td>Sodium - Nickel Chloride (ZEBRA: Z5-278-ML3C-64)</td>
<td>Vanadium – Redox (VRB: FB10 - 100)</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Minimum: 260 °C</td>
<td></td>
<td>Maximum: SOC dependant</td>
</tr>
<tr>
<td>Maximum: SOC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Auxiliary Systems

<table>
<thead>
<tr>
<th>Battery Management System consume (W)</th>
<th>10 (&lt; 0.1% $P_{nom}$)</th>
<th>100 (= 1% $P_{nom}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power Auxiliary Consume (for Battery)</td>
<td>Cooling Fan: 60 W (&lt; 0.4% $P_{nom}$) (temperature threshold see figure)</td>
<td>Circulating pumps: 15% Battery kWh capacity/24h → 625 W (= 6% $P_{nom}$) (note: pumps inverter driven → the consume is α to the Vanadium flow → α Current, see Look-up Table)</td>
</tr>
<tr>
<td></td>
<td>Heater: 190 W (= 1% $P_{nom}$) (temperature threshold 260 °C)</td>
<td></td>
</tr>
<tr>
<td>Cooling fan thermal power</td>
<td>Convective Coeff. 30 W/K → $\Delta T = 300^\circ C$ → removed thermal power = 9000 W$<em>{in}$ (note: @ I = 64 A &amp; $R</em>{tot}$ = 0.826 Ω → $P_{joule}$ = 3400 W$<em>{th}$) @ I = 128 A &amp; $R</em>{tot}$ = 0.826 Ω → $P_{joule}$ = 13500 W$_{th}$)</td>
<td>None</td>
</tr>
<tr>
<td>(based on the convective heat transfer coefficient)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- $P_{nom}$: Nominal Power
- $R_{tot}$: Total Resistance
- $P_{joule}$: Joule Power
- $P_{th}$: Thermal Power