A Model of a Battery Energy Storage System for Power Systems Stability Studies

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Abstract—The electric power systems, which are responsible for energy transportation in the form of electricity, are subject to a number of disturbances such as frequency variations or voltage fluctuations. These situations can influence the power quality, bringing a negative impact to the devices that we connect to the network.

An effective energy storage, such as Battery Energy Storage Systems (BESS), is able to bring to the network many advantages, not only in power quality applications that increase network security but also in energy management applications that enables efficient response to fluctuations demand and increased use of renewable energy.

Batteries, as auxiliary network element, exhibit unique characteristics of performance, efficiency and versatility, especially the lithium-ion's.

The modeling of this technology is a complex process because even the battery characteristics are easily influenced by external factors. However, the chosen model intends to represent not only the various physical phenomena present but also the influence of the BESS in power systems.

Index Terms—Battery, BESS, Battery modeling, Energy Quality, Microgrids.

I. INTRODUCTION

T HE eletric system became the basis of modern society, without any prospect of slowing down [1].

Renewable energies have arised as a solution to the growing energetic needs of society, taking into account environmental concerns and the need to get low cost energy. However, the integration of this type of distributed generation features several challenges [2,3].

A microgrid is made up of a set of distributed generation sources and end customers of electrical energy, interconnected by a small electrical grid of medium or low voltage. The microgrid is scaled with the purpose of owning enough resources to supply the connected customers, and it is regarded by the electrical grid upstream as a single customer [4]. Nevertheless, the network keeps on being fragile, subject to a number of disturbances such as fluctuations in frequency or voltage variations.

In order to take full advantage of renewable energies and mitigate their problems, such as the variability and intermittency of the resources that influence the stability of the grid, it is advisable to implement an energy storage system such as the BESS.

The BESS versatility makes them useful at any stage of generation, transmission and distribution of energy, fulfilling in each of them a different purpose, but having in common the possibility of increasing the networks safety and reliability.

This technology has various applications, such as:

A. Capacity firming

The variable, intermittent power output from a renewable power plant, such as wind or solar, can be maintained at a comitted (constant) level for a period of time.

The energy storage system smothes the output and controls de ramp rate (MW/min) to eliminate rapid voltage and power swings on the eletrical grid [5].

B. Frequency regulation

The energy storage system is charged or discharged in response to an increase or decrease, repectively, of grid frequency.

This feature is particularly welcome because it not only relieves the plants from having a frequency regulation device as continues to ensure the quality of energy to customers [5].

C. Load leveling

Load leveling usually involves storing power during periods of light loading on the system and delivering it during periods of high demand. During these periods of high demand the energy storage system supplies power, reducing the load on less economical peak-generating facilities.

Simultaneously, load leveling allows the postponement of investments in grid upgrades or in new generating capacity [5].

D. Peak shaving

Peak shaving is similar to load leveling, but may be for the purpose of reducing peak demand rather than for economy of operation. The goal is to avoid the instalation of capacity to supply the peaks of a highly variable load. Peak shaving instalations are often owned by the electricity consumers, rather than by the utilities.

Economically, commercial and industrial customers would save on electricity bills if the peak demand was successfully reduced. Companies would reduce generation operating costs during peak periods - reducing the need for the existence of tip power plants. Finally, there may be a delay in investment in infrastructures because the loads are smoother and peaks are smaller [5].

E. Power quality

In power quality applications, an energy storage system helps protect downstream loads against short-duration events that affect the quality of the energy delivered.

A storage system has value in this application as it provides backup power to sensitive electronic devices and microprocessor-based controllers.

F. Spinning reserve

To provide effective spinning reserve, the energy storage system is maintained at a level of charge ready to respond to a generation or transmission outage.

Depending on the application, the system can responde within miliseconds or minutes and supply power to maintain network continuity while the back-up generator is started and brought online. This enables generators to work at optimum power output without the need to keep idle capacity for spinning reserves. It can also eliminate the need to have back-up generatores running idle [5].

II. Batteries

In its core, batteries are a group of eletrochemical cells that convert chemical energy into eletrical energy. Each cell is composed by an anode, a cathode and an electrolyte [6].

The standart potential of a cell depends on the nature of its active materials, and the usefull capacity depends on its quantity. The pratical voltage and capacity are diferent from the theoretical, since there are several secondary phenomena that introduce losses, and which define eletrochemical efficiency. These phenomena are explained next and represented in Figure 1.
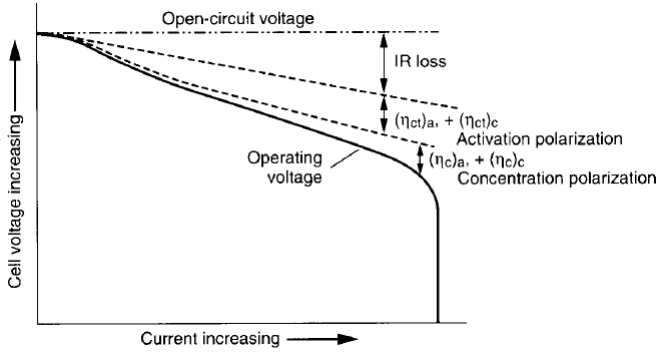

Figure 1: Cell losses a function of operating current [6]

The voltage on a cell may be given by:

$$E = E^0 - [(\eta_{ct})_a + (\eta_c)_a] - [(\eta_{ct})_c + (\eta_c)_c] - i.R_i = iR \quad (1)$$

E_0 – Open circuit voltage, OCV
i – Operation current
R_i – Internal resistance
$\eta_c)_a$ e $\eta_c)_c$ – Polarization due to concentration gradients
$\eta_{ct})_a$ e $\eta_{ct})_c$ – Polarization due to activation, and charge transference.

The dominant losses are the double layer capacity, the charge transfer, the difussion and the ohmic impedance [6].

In addition, the performance of the batery is also affected by the voltage level, the current, the temperature, the operation mode (charge or discharge) and the age.

III. Modelation

The need to implement a model that describes the behavior of a battery is directly related to the fact that the batteries are, normally, the weakest link in the electric power system chain.

Therefore, a model able to predict longevity and performance of a battery can be used in the construction of viable systems at an energetic level, in the improvement of the systems performance and to predict their own longevity for different load profiles, making it possible to increase their efficiency.

A. Proposed model

At a macroscopic level, a model has to be able to describe several key behaviors:

- Voltage, which results from the contribuition of the several cells.
- Current, defined by external device or connection.
- Capacity, defined by the quantity of active materials in reagent form.
- State of charge, defined by the quantity of active materials in reagent form.
- Impedance, that represents the relation between the voltage and current.
- Losses, that represent the electrochemical efficiency in energy conversion.

The main problem on battery modeling is that some variables need to be estimated [7,8]. From the enumerated topics above, only the voltage and the current can be measured. All the others need to be estimated. In addition, these variables depend on each other and from external factors like temperature and age [9].

The implemented model was initially proposed by Chen and Rincon-Mora [9] and was chosen due to its precision and simplicity (Figure 2).
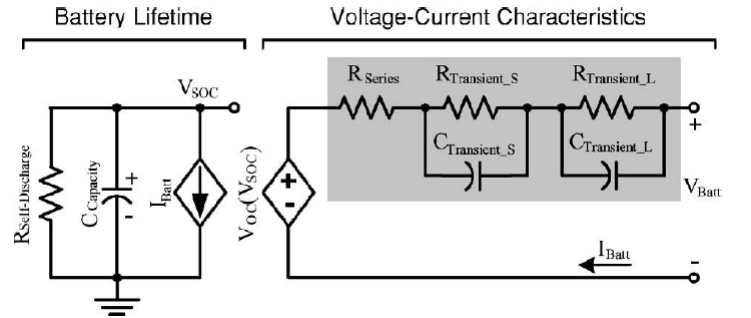

Figure 2: Proposed battery model [9]

On the Battery Lifetime circuit, the battery capacity is represented by the capacitor $C_{capacity}$, where the voltage is normalized to 1V. The fully charged capacitor represents a fully charged battery (100% SOC). The voltage at the capacitor represents the state of charge. The dependent source current intends to represent the current required by the load. The self discharge phenomenon is represented by the $R_{self-discharge}$.

On the Voltage-Current Characteristics circuit, the dependent voltage source defines the open voltage as a function of the state of charge. The dynamics on a battery can be divided as fast and slow. In the models, the parameter R_{series} represents the fast dynamic and the RC loop the slow one

(mainly due to the diffusion process). Lastly, the losses are modeled by R_{series} and $R_{transient}$.

B. Parameters estimation

The data provided in the catalogs of the batteries are not sufficient to derive all the parameters that the model requires. As mentioned above, the parameters of the model are obtained from experimental tests specific to each battery. As this is a complex and lengthly process it was decided to use the extrated parameters from a lead-acid battery by Reis [10].

The parameters are described below:

1) Open circuit voltage:

$$V_{oc_{dis}}(SOC) = -0.7647(SOC)^2 + 2.6527(SOC) + 11.459 \tag{2}$$

$$V_{oc_{char}}(SOC) = -1.5318(SOC)^2 + 2.9403(SOC) + 12.087 \tag{3}$$

2) R_{series} :

$$R_{s_{dis}}(SOC) = 0.175(SOC)^2 - 0.2885(SOC) + 0.2674 \tag{4}$$

$$R_{s_{char}}(SOC) = 1.2427(SOC)^2 - 0.8369(SOC) + 0.1885 \tag{5}$$

3) $R_{transient}$:

$$R_{t_{dis}}(SOC) = 0.2673(SOC)^2 - 0.3216(SOC) + 0.1386 \tag{6}$$

$$R_{t_{char}}(SOC) = 1.8185(SOC)^2 - 1.012(SOC) + 0.168 \tag{7}$$

4) $C_{transient}$:

$$C_{t_{dis}}(SOC) = -5050.1(SOC)^2 + 3841.7(SOC) + 1287.3 \tag{8}$$

$$C_{t_{char}}(SOC) = -10939(SOC)^2 + 7373.4(SOC) + 3711 \tag{9}$$

C. Model simulation

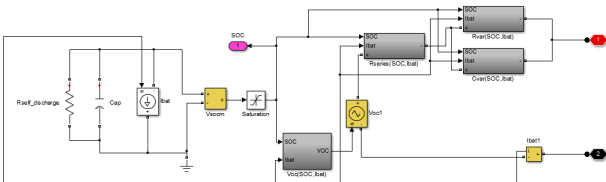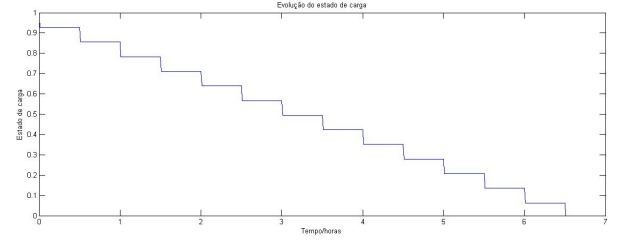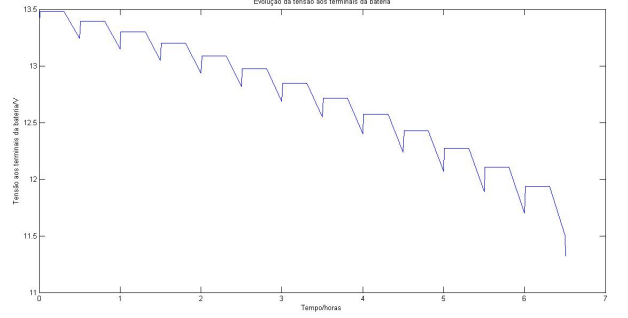The proposed model in Figure 2 is implemented in *Simulink* in Figure 3.

Figure 3: Battery model in *Simulink*

(a) State of charge

(b) Battery voltage

Figure 4: State of charge and battery voltage on a discharge operation

1) Simulation in DC regime: In order to validate the model, the following situation was simulated – a 2A.h battery is connected to a load that needs to be fed hourly during 30 minutes.

In figure (5b) it is visible the near absence of the slow dinamic. This is due to the values of the RC loop being so low that the current nearly ignores the capacity which would give the decrescent exponential form to the wave.

The way of thinking for the charging operation was very similar to the discharge – a voltage source charges a 2A.h battery, initially empty, hourly during 30 minutes.

Then again it can be confirmed the near absence of the slow dinamic. To revert this situation it would be necessary to modify the circuit raising the values of the capacitor $C_{transient}$ through the equations (8) and (9).

2) Simulation in AC regime: A battery feeding a three phase RL load was simulated in order to evaluate the battery behavior in AC regime. This situation is quite common when the main purpose of the BESS is to maintain the power quality. In this case, the load can represent the stator of an asynchronous machine, for example. Furthermore, it was necessary the implementation of a DC/AC inverter controled by PWM and a transformer to elevate the battery's voltage from 12V to the 400V that are needed to feed the machine.

Just as expected, the battery is supplying energy to the load during all the simulation time (Figure 6). Although the voltage required by the load is 230V (RMS value), the battery does not discharge abruptly. This behavior is due to the simulation time being short (0.2s), which is a value close to the one's used in a real situation.
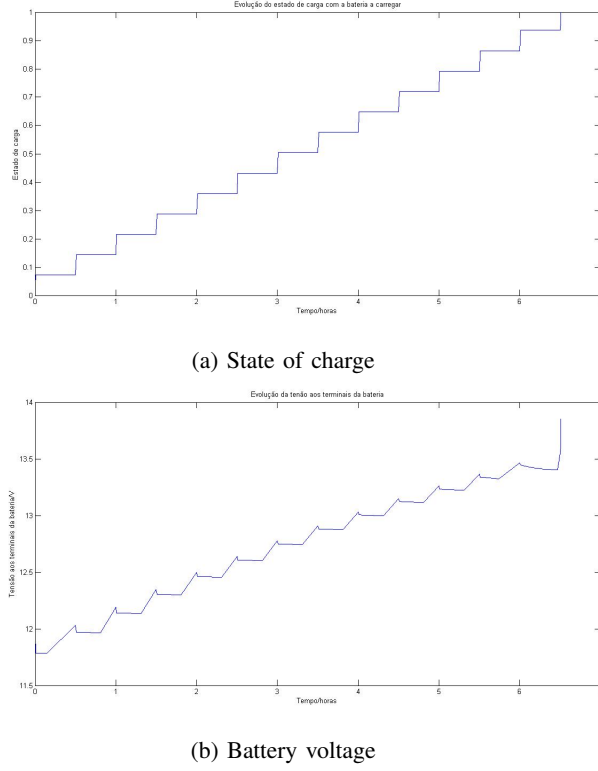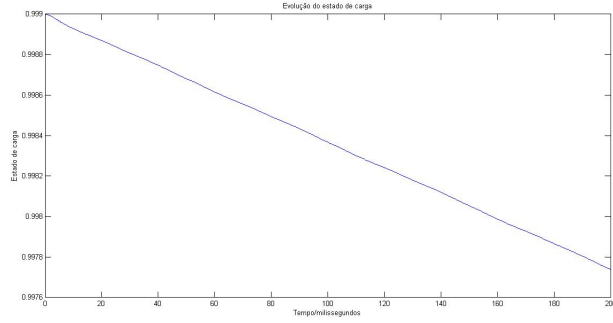
(a) State of charge

(b) Battery voltage

Figure 5: State of charge and Battery voltage on a charge operation

Figure 6: State of charge for the AC regime

(a) State of charge

(b) Battery voltage

Figure 7: State of charge and Battery voltage when running

(a) State of charge
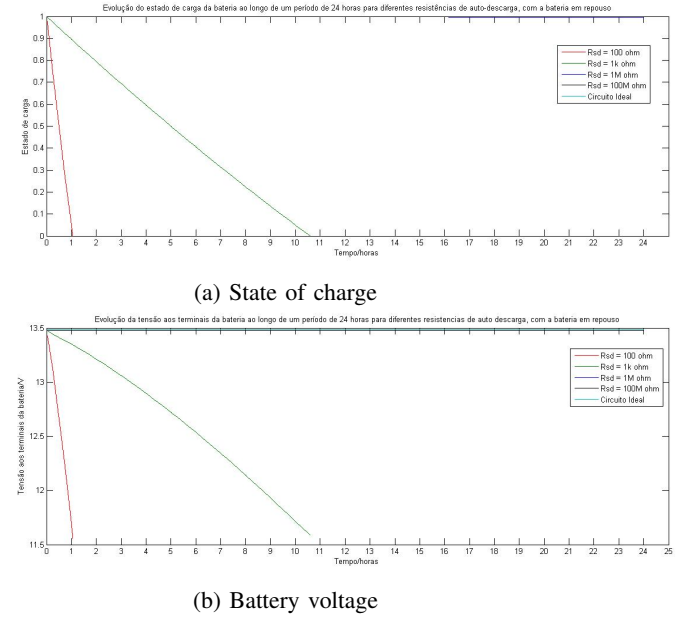
(b) Battery voltage

Figure 8: State of charge and Battery voltage when at rest

D. Performance at real conditions

The self-discharge resistance, despite being ignored in short term simulations because of its high value, makes sense to be studied for long time intervals since the battery may be at rest for hours. Furthermore, the actual battery capacity will decrease over time due to the irreversible secondary reactions taking place, turning the material from active to inactive. These reactions are favored in certain voltage, temperature and charge state situations.

1) Self-discharge Resistance: Looking back at Figure 3, in battery standby times the capacitor representing the battery capacity will discharge through the resistance, losing its stored energy.

In order to assess the impact of the self-discharge resistance, the normal operation and the no-load were simulated. For each one, the simulation time was 24 hours during which the 2A.h battery should discharge hourly during 30s.

In Figure 7a the slope of the steps that mold the waveform of SOC decreases as the $R_{self-discharge}$ increases. This indicates that the battery loses energy during the rest periods due to self-discharge resistance. It is also possible to check that the voltage diminishes as the resistance increases (Figure 7b).

As expected, the lower the self-discharge resistance value is, sooner the battery empties. However, the self-discharge resistance value is not a tabulated value since it depends on where the battery operates or is stored.

2) Real capacity: In the *Simulink*, the capacitor defines both the SOC limits and the actual state. In order to model the behavior of a real capacity that loses its characteristics

through time it is not enough to just change it into a variable capacitor, since each iteration would create new values for the SOC limits. Therefore, the way found to modelate this component is to act upon its genesis, the SOC value:

$$SOC_{real} = SOC\left(1 - [cicles \div Lifespan]\right) \qquad (10)$$

All the process was simulated in DC regime to facilitate the process. The system intended to evaluate the battery behavior on 24 hours in which the battery was supplying a 100W load during 45 minutes and being fed, afterwards, by a voltage source of 15V during 15 minutes.

Normally the lifespan of the battery is comprized between 2000 and 5000 life cicles. In this case the life cicles were reduced to only 20 in order to see the behavior faster.

(a) Ideal capacity
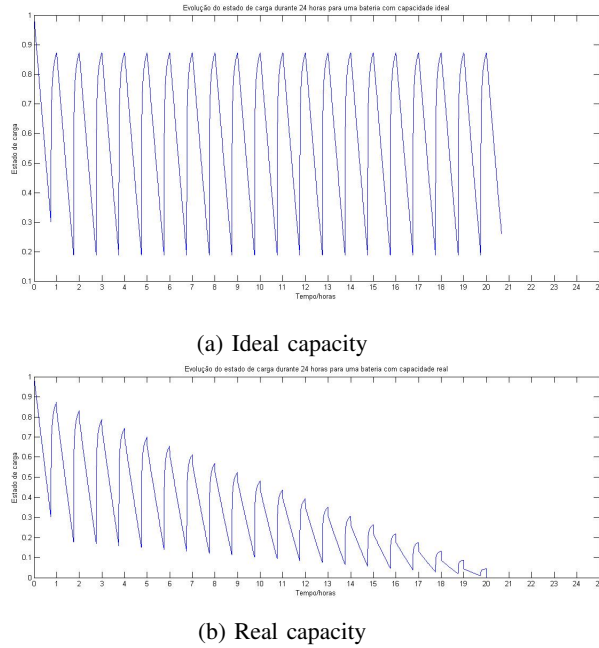
(b) Real capacity

Figure 9: State of charge when the capacitor is real or ideal

Figure 9a shows the ideal capacity, no matter how much time passes the capacitor is always capable of fully charging. In the other hand, Figure 13b demonstrates the non-ideality that happens in reality where for each cycle the maximum value of the capacity diminishes. As shown the battery's lifespan given by the manufacturers is extremely important since it has a great impact through time on the overall battery perfomance.

IV. POWER SYSTEMS

BESS are generally connected to the rest of the system at the point of common coupling (PCC) via power-eletronic interfaces such as bidirectional DC-DC converters and voltage source converters (VSCs). The DC-DC converter is used to increase the voltage level from the battery into the DC-Link and the VSC is used to convert power from DC to AC [11].

Figure 10 shows the configuration of a converter-connected BESS. A buck/boost converter is used to stabilize and maintain
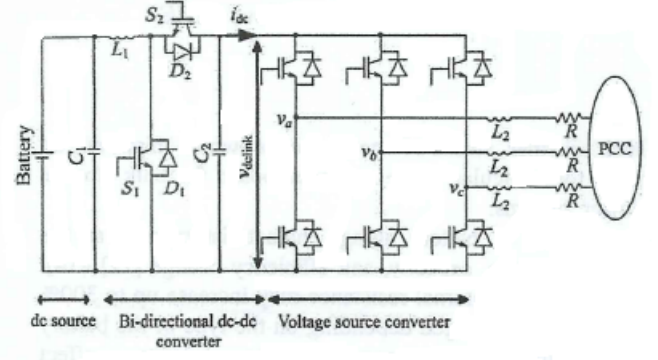

Figure 10: Configuration of a BESS for connection to the PCC [11]

the voltage of the DC-link of the VSC, despite the exchange of real power to/from the grid [11].

The VSC is controlled by a decoupled control method in a dq0 frame, wherein the exchanged real and reactive powers are controled independently [11]. A pulsewidth modulation (PWM) method is then used to craft the required voltage at the VSC terminals.
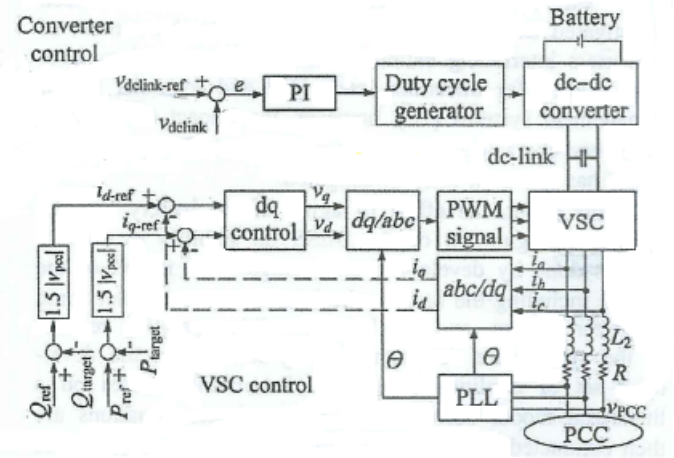

Figure 11: Control strategy of a BESS for PCC connection [11]

Figure 11 shows a schematic control diagram of the system shown in Figure 10. As seen, a separate loop for the DC-DC converter is used to stabilize the voltage of the DC-link. This loop uses the voltage of DC-link as feedback and calculates the duty cycle of the DC-DC converter. Then the converter changes the terminal voltage of the batteries to charge or discharge with an appropriate current to meet the system's power requirements [11].

Although this method was not fully followed, it served as inspiration to develop the one that ended up being implemented. Figures 12 and 13 show the final implementation of the power-electronics interface in *Simulink*.
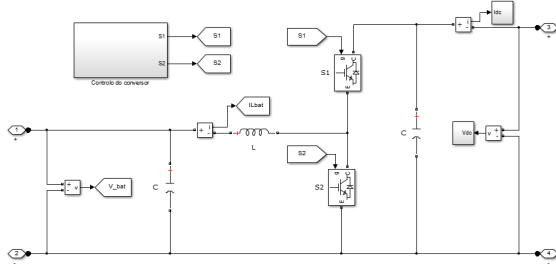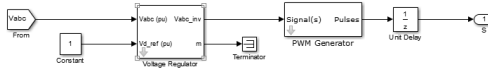
(a) Buck/boost converter in *Simulink*
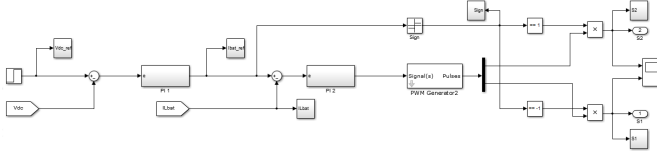
(b) Converter control

Figure 12: DC-DC converter and its control
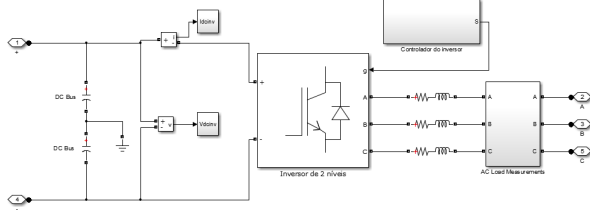
(a) Two level VSC

(b) Inverter control

Figure 13: VSC implementation and its control implemented in *Simulink*

V. MICROGRID

Each microgrid is designed to have sufficient resources, distributed generation sources, to meet local demand and is considered as a single customer from the point of view of the main network.

The microgrid has the peculiarity of being able to turn itself off from the rest of the grid, operating autonomously whenever needed, which becomes a gain in terms of economy and of power quality for the customers linked to the microgrid. However, it implies additional attention in these handling, since they cause unforeseeable imbalances between the generation and the loads, which may imply the introduction of additional technology to prevent the transitory stage reaches the end customer.

Typically, the renewable energies used are: solar panels, mini-hydrics and wind turbines. Other types of distributed generations are used such as gas microturbines with and without cogeneration systems (CHP), or even diesel generators.

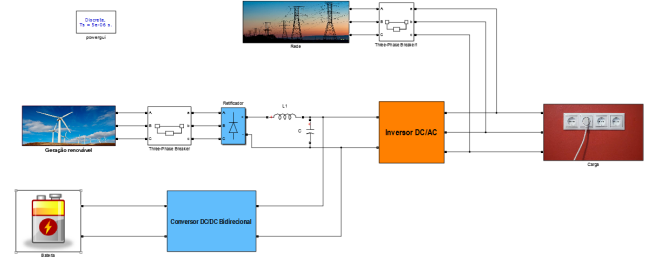Figure 14 shows the dimensioned microgrid used to study the BESS behavior.

Figure 14: Microgrid

The load is initially a 1kW resistance, and 0.25s later an adittional 100kW and 100VAR RL load is added.
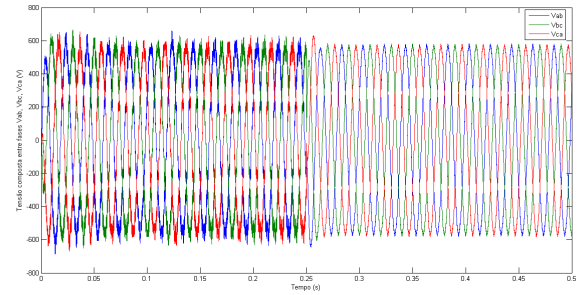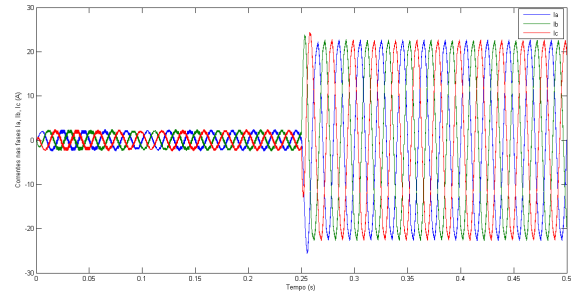

Figure 15: Voltage between phases
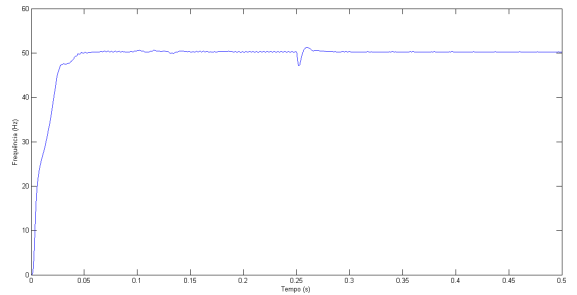

Figure 16: Currents in the load phases

Figure 17: Grid frequency

The introduction of the RL load caused a smoothing in the voltage (Figure 15) and current (Figure 16) waveforms. This was due to the inductance characteristics.
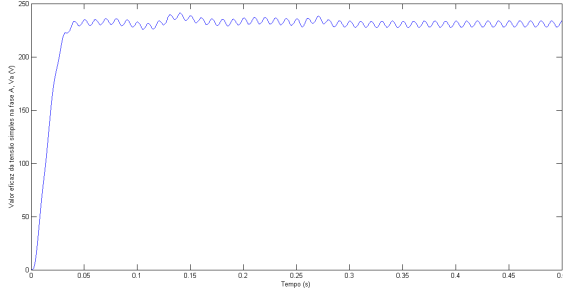
Figure 18: Voltage in phase A

Figure 20: State of charge when a disturbance in the load occurs

Through Figure 18 we are able to validate the VSC voltage regulator since it maintained the voltage at the load during its variation, leaving the effects to manifest through the currents amplitude.

The load variation introduced a transient in the frequency (Figure 17) that was rapidly corrected by the BESS.

1) Load disturbance: During peak hours the BESS assumes the role of balancing the frequency oscilations that can happen during short periods of time.

To mimic a load variation, a 1MW load was forced to connect with the initial 1kW load.

As determined by an international standard (EN 50160), the acceptable frequency limits are set between 49.95 and 50.05 Hz.

Figure 19 shows the eficient work of the BESS balancing the frequency values, providing energy quality to the network customers. Furthermore, it can be seen that if the lower frequency limit is violated the battery starts to supply power. In the other hand, if the superior limit is violated the battery absorbs power.
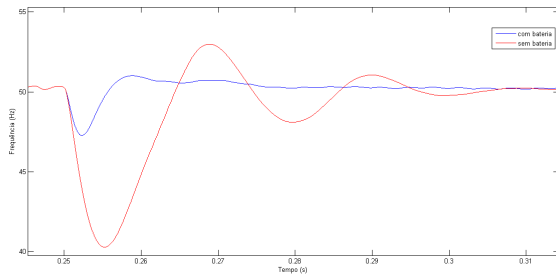
In this case, the battery just had to run one discharge (Figure 22) due the violation of only the lower frequency limit.

Figure 21: Frequency when a disturbance in the load occurs

Figure 19: Frequency when a disturbance in the load occurs

Figure 22: State of charge when a disturbance in the generator occurs

2) Generation disturbance: In order to enable microgrids to operate in isolated mode they first have to be disconnected from the main grid, which in itself introduces a transient stage in the system. There also must exist a distributed generation source ready to sustain the system's load.

The battery role is to balance the energy between the disconnection from the main grid and the full capacity of the distributed generation.

Similarly, as it happens when the load varies, the battery comes into operation when there are oscilations in the frequency (Figure 21).
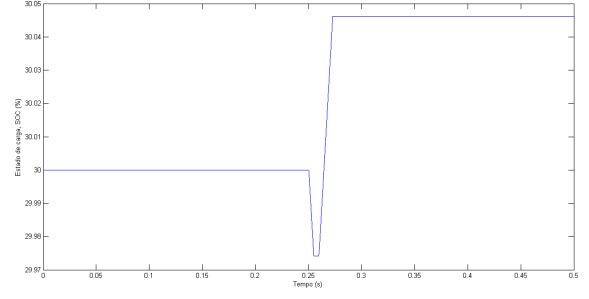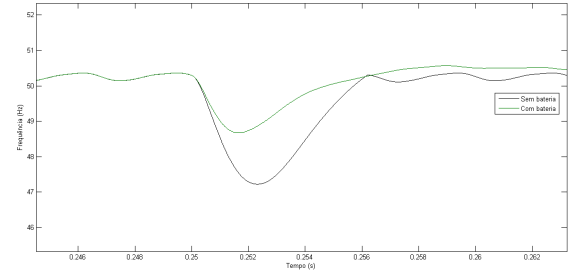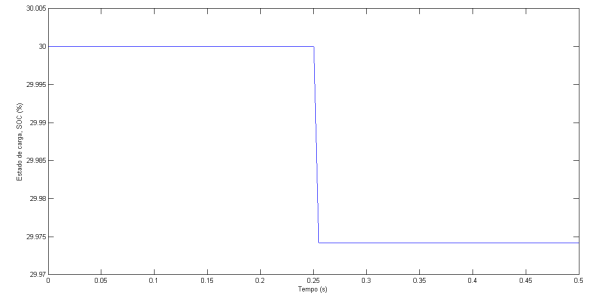
3) Load regulation: Such situation may occur during a peak shaving operation. In order to evaluate the BESS behavior, a system in which it partially shuts off the load was simulated, provoking an excess of energy in the system. A where the load suffered a rise was simulated, making the load unable to be fed by the actual generation.

The results confirm the possibility of the BESS functioning as a load regulator. As it can be seen in Figure 23, if the value of the load is higher than the value of the generation source, the battery should help the energy source. In the other hand, when the load value is inferior to the generation value (Figure 24), the battery absorbs energy, functioning as a load.
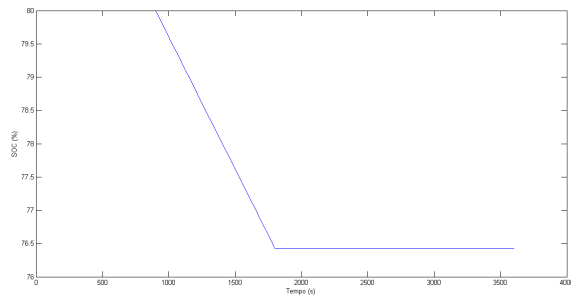
Figure 23: State of charge of the battery when there is a deficit in the generation
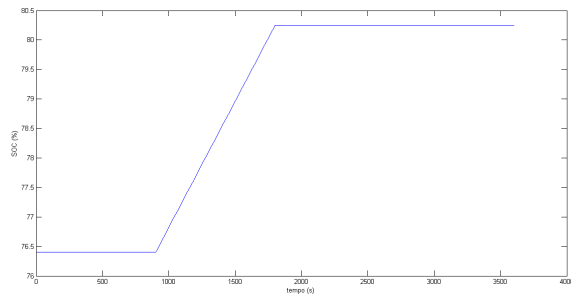

Figure 24: State of charge of the battery when there is a excess of energy in the system

VI. CONCLUSION

The need to implement a model capable of describing the behavior of a battery is directly connected with the fact that, normally, the energy storage systems are the weakest link in the power systems.

The model predicts, with success, the over time loss of battery capacity. This capacity loss is due to a prolonged storage (or non utilization of the battery) or the consumption of the battery's life cycles during the charge/discharge operations.

The model was submitted to the most varied tests, both in charge and discharge operations, and AC and DC regime in wich revealed the model's aptitude to represent the behavior of a battery.

Relatively to microgrids, it was possible to confirm the battery's effectiveness has a viable solution to some of the microgrids problems, such as the frequency variations. Furthermore, this technology is useful as a load regulator, balancing the generation with the demand at any moment.

Based on every result, it is possible to conclude that the implemented model is credible and satisfies the purpose to simulate, with some detail, the physical phenomena that occurs inside the batteries and the influence of the BESS in the power systems.

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