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Modelo dinámico de batería de sodio sulfuro para su aplicación en microredes

Dynamic model of sodium sulphur battery for application in microgrids

Antonio E. Sarasua, Marcelo G. Molina, Pedro E. Mercado

Resumen

Hoy en día, además de la tendencia a utilizar fuentes renovables de energía, existe también una tendencia a operar estas unidades en una forma descentralizada de modo que sean capaces, si es necesario, de trabajar independientemente o en forma aislada del resto del sistema de potencia. Estos sistemas se denominan microredes (MGs). Cuando se utilizan fuentes de energías renovables, basadas principalmente en la radiación solar o el viento, el problema que normalmente se enfrenta son las fluctuaciones y la naturaleza intermitente de estos recursos. En el caso de las MGs este problema es particularmente crítico dada la capacidad que deben tener de trabajar en forma aislada. Para operar con seguridad la MG normalmente se utiliza una combinación de varios tipos de generadores y también se hace uso de almacenamiento de energía para mantener el equilibrio de la potencia activa. Entre los nuevos sistemas de almacenamiento, las baterías de sodio-sulfuro (NAS) se consideran adecuadas para llevar a cabo diversas tareas de seguridad en las MGs. Las baterías del tipo NAS tienen son capaces de almacenar gran cantidad de energía y densidad de potencia por unidad de volumen y también pueden proporcionar energía tanto en el corto como en el largo alcance. Sin embargo, el inconveniente que estas baterías tienen es que hay pocos modelos que representan fielmente su comportamiento dinámico. Para un estudio adecuado de la seguridad de MGs usando baterías tipo NAS, es necesario identificar el comportamiento dinámico de estas baterías con un modelo preciso. Este artículo presenta el modelado detallado y simulación dinámica de un dispositivo de almacenamiento tipo NAS para su uso en microredes. También se describe el sistema de acondicionamiento de potencia (DSTATCOM) que se utiliza para conectar la batería NAS con la MG y la estrategia de control. Por último, el modelo de la batería NAS se implementa en el entorno de MATLAB / Simulink, poniéndolo a prueba en una microred.

Palabras clave: Baterías de sodio sulfuro (NAS); Microredes; Modelación detallada; Sistemas de acondicionamiento de potencia; Técnicas de control.

Abstract

Nowadays, in addition to a tendency to the use of renewable energy sources, there is also the tendency to operate these units in a decentralized manner so that they are able, if necessary, to work independently or in isolation from the rest of the power system. These systems are called microgrids (MGs). When using renewable energy sources, mainly based on solar radiation or wind, the problem is mainly the fluctuating and intermittent nature of these resources. In the case of MGs, this problem is particularly critical given the need of the ability to work in isolation. To operate MGs safely, a combination of several types of generators and also energy storage should be used to maintain the balance of active power. Among the new storage systems, sodium sulphur batteries (NAS) are considered suitable to perform various security tasks in MG. NAS batteries have a high energy and power density per unit volume and they can also provide energy in both the short and long range. However, the disadvantage of these batteries is that there are few models that genuinely represent their dynamic behavior. For a proper study of the security of MGs using NAS battery, it is necessary to identify their dynamic performance with an accurate model. This paper presents the detailed modeling and dynamic simulation of a NAS battery storage for use in MGs. It also describes the power conditioning system (DSTATCOM) used to connect the NAS battery with the MG and the control strategy. Finally, a NAS battery model was implemented in the environment of MATLAB/Simulink, and then tested in a microgrid system.

Keywords: Sodium sulphur batteries (NAS); Microgrids (MG); Detailed modeling; Power conditioning system; Control techniques.

Introduction

At present, power utilities generate electricity using mainly traditional non-renewable energy sources, such as fossil (i.e. coal, oil and natural gas) and nuclear fuels, with their associated environmental hazards. The availability and the storage form (back-up capacities) of these electric energy sources help, for instance, maintain a spinning reserve in power systems with minimum risk. Electric power produced by renewable energy sources (RES) distributed around the power grid is increasingly attracting a lot of attention worldwide. RES-based distributed generation is considered to be important mainly to reach two goals: to reduce the dependency on fossil fuels and to reduce the emission of greenhouse gases from fossil fuel combustion.

From a wide range of renewable energy resources, wind and solar energy are the focusing sources in this work. Reasons to choose them are found on their plentiful availability according to site, almost null commodity costs, and low or null ecological impact. Major drawbacks, however, are the unpredictability of generated power and the constrained back-up capacities. Unfortunately, the power generated from sun and especially from wind has a low availability factor. The ratio between the rated generation power and the effective output energy fluctuates because of climatic factors, such as solar radiation or wind speed variations. The generated power output may vary not only seasonally or daily, but also from small variations of wind speed or solar radiation within an hour or some minutes. Back-up capacity constraints are referred to the impossibility to store solar of wind energy as such. The generated electric power output is thus not only unpredictable but also it may arise and peak in periods when systems operators do not require it. Therefore, this energy is prone to be wasted or discarded.

In order to solve the unpredictability and the back-up problems, energy storage systems may be coupled with RES-based DG and operated together as distributed energy resources (DER) for compensating the intermittent nature of RES-based DG sources and thus helping improving the short term planning. Energy storage systems used in this way, enable a better management of RES-based DG by means of smoothing the power output, for performing reactive compensation, load following or for increasing spinning reserve [1]. When RES-based DG has enough storage capacity they can operate as a microgrid without a connection to main power system when necessary.

This work analyses the general characteristics of sodium-sulphur batteries and their usage and effectiveness in storage systems for MGs. Then, a sodium-sulphur battery model is implemented and tested in the environment of MATLAB/Simulink, and then also tested in a microgrid system.

Sodium-Sulphur Batteries

General Description

In April 2002, TEPCO (www.tepco.co.jp) and NGK (www.ngk.co.jp) Insulators Ltd announced the commercialization of their sodium-sulphur battery product lines in Japan, in addition to their intent to introduce products globally [2]. At present, the joint NGK-TEPCO is the most important vendor of sodium-sulphur batteries for utility applications, and the technology described in this paper relates to NGK-TEPCO's sodium-sulphur battery modules (NAS®, registered in Japan).

A sodium-sulphur battery uses sodium and sulphur as the anode and cathode respectively, while a beta-Al_2O_3 ceramic tube acts as both the electrolyte and separator simultaneously. This battery works on the principles of the electrochemical reaction between sodium and sulphur and the formation of sodium polysulfide.

Figure 1 illustrates the tubular design of a sodium-sulphur battery with a central sodium electrode [3-4].

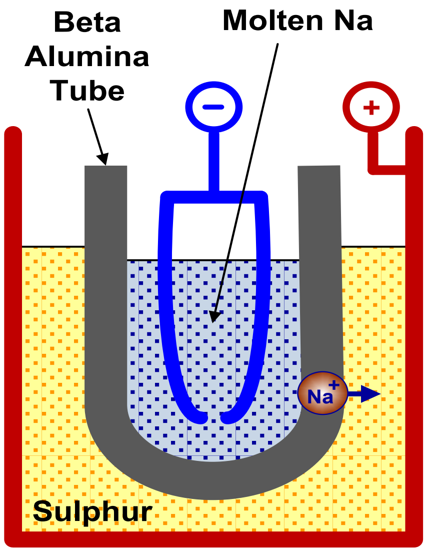

Figure 1: Schematic model of a sodium-sulphur battery.

The open circuit voltage of the cell at 350°C is 2.075 V. The NAS battery usually works at a temperature ranging between 300°C and 350°C, at which sodium and sulphur, as well as the reaction product polysulfide exist in liquid state, which supports the high reactivity of the electrodes. Thermal control from a high-temp system is a built-in feature of the battery and it presents no specific usage or safety problems [5].

The specific energy density of the battery reaches 760 Wh/kg at 350°C, nearly three times that of a lead acid battery, leading to designs of about one third the space required for the lead acid battery for similar commercial applications.

Electrical behaviour

NAS batteries have a pulse power capability of over five times the continuous rating (for 30 seconds). This pulse-power capability is also available even if the unit is currently in the middle of a long term discharge for peak saving (PS). This attribute enables the battery to be economically used in combined power quality (PQ) and PS applications [2]. They are competitive in combined function applications of a few seconds or several hours. The ability to inject power for short periods is useful to mitigate voltage sags or momentary outages and sufficient amount to address the majority of PQ events and to support a transition to a backup generator [6].

Through adequate cells arrangements (series or parallel arrays) the battery modules can then be optimized for PQ or PS service in different values [7]. Typical modules for PS have 320 cells and a rated capacity of 360 kWh [8]. The nominal operating voltage of these modules are 700Vdc but terminal voltage varies between 325V and 790V hanging on state and direction of charge. Each module has current ratings of up to 810Adc [2-5].

Either PQ and PS modules are charged to 50kW, but each variant is discharged at a different rate, thereby giving a different charge/discharge ratio depending on design and market role. The PQ-G50 NAS battery module can discharge at up to 250 kW for 30 seconds in addition to discharging at lower power levels for longer periods of time [9].

The NAS battery resistance varies with the temperature, i.e. the higher the module temperature, the smaller the internal resistance becomes [7]. The effect of temperature on the internal resistance is very important as it determines the limit to the battery's peak power output.

The battery voltage in open circuit (Voc) of NAS battery depends mainly on the state of discharge (SOD). Due to the composition reaction, the Voc of NAS battery is relatively constant but drops linearly after 60-75% SOD, as shown in Figure 2.

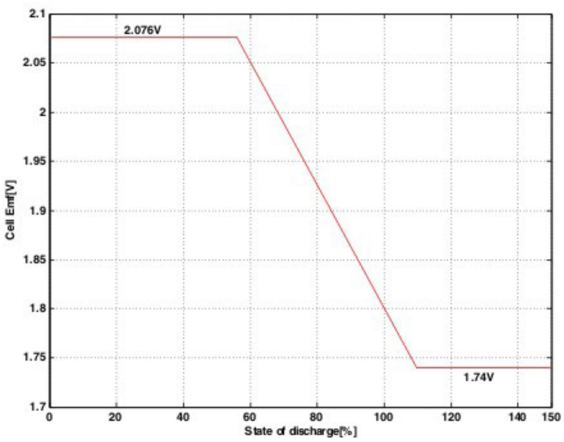

Figure 2: Voltage variation as a function of SOD for NAS-type battery cell [7].

Additionally, as shown in Figure 3, depending on the depth of discharge and temperature, the internal resistance of the cell can varies four times (from 1 to 4 mΩ).

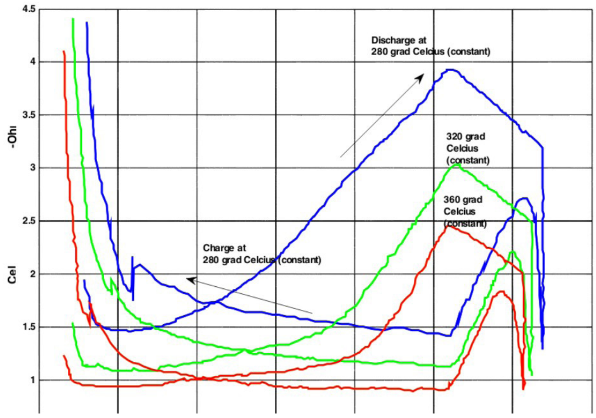

Figure 3: Internal resistance variation depending on the state of charge/discharge for various temperatures in a NAS-type battery cell (experimental from [7]).

Nas Battery Model

The development of a battery model should take into account that the internal resistance and open circuit voltage of a NAS battery model cannot be considered constant. In addition, the resistance must have different values depending on charge direction. These especially complex features and the restrictions from NGK-TEPCO to give information about their product, turns difficult to obtain a dynamic model of a NAS battery.

The model tested in [7] is considered the best suited to model a NAS battery. This model takes into account the non-linear battery element characteristic during charging and discharging as well as the internal resistance dependence and battery's open-circuit voltage (Voc) like a function of SOD.

To model a NAS battery module only for PQ purposes, the NAS battery model can be modified on the basis of [7]. For short periods, the temperature can be considered constant and the effects of charge-discharge lifecycle resistance can be neglected. To implement a NAS battery model in MATLAB/Simulink, the SimPowerSystems toolbox [10] is the best suited for the proposed model, but variable resistances cannot be modelled. The authors have implemented a special procedure to model the variability of the internal resistance and Voc.

Figure 4 shows a schematic of the NAS battery model developed and implemented with SimPowerSystems toolbox.

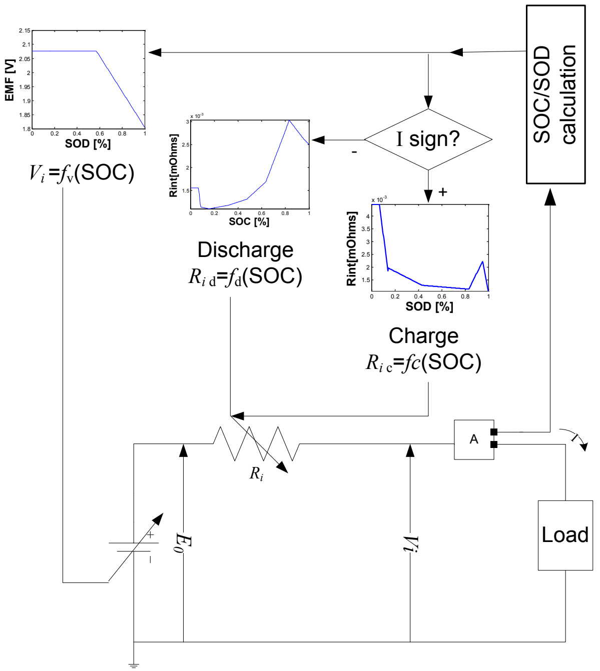

Figure 4: Schematic circuit of the NAS battery model implemented

The NAS battery model was tested using a cell with a single resistive load to validate the model. Figures 5 and 6 shows the variation of internal resistance to change of SOD for discharging and charging, respectively, in a cell type T5 to 320ºC. Figure 7 shows the Emf vs. SOD.

The NAS battery model can be easily modified to simulate the temperature variation to work in PS mode.

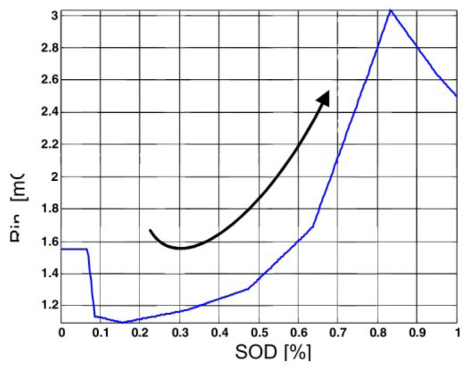

Figure 5: Internal cell resistance vs. SOD at 320 ºC for a discharge situation (Simulated)

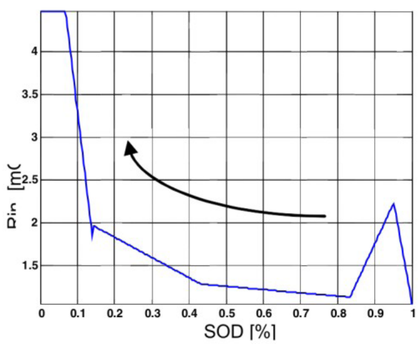

Figure 6: Internal cell resistance vs. SOD at 320 ºC for a charge situation (Simulated)

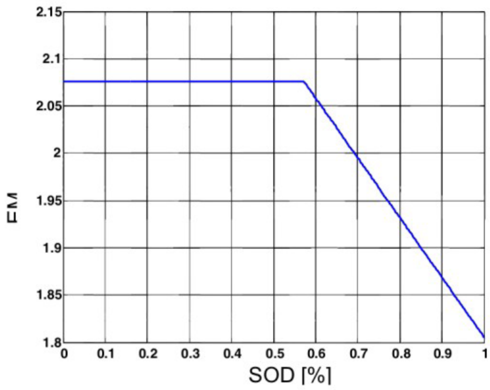

Figure 7: Cell electromotive force vs. SOD (Simulated)

Dstatcom for microgrids with nas battery (dstatcom/nas)

A distribution static compensator or DSTATCOM is a fast response, solid-state power controller that provides flexible voltage control at the point of connection to the utility distribution feeder for PQ improvements. If energy storage is included into the dc bus, the DSTATCOM can also be used for PS improvements. A DSTATCOM with a battery can exchange both active and reactive power with the distribution system by varying the amplitude and phase angle of the converter voltage with respect to the line terminal voltage. The result is a controlled current flow (P or Q) through the tie reactance between the DSTATCOM and the distribution network in instantaneous real-time [11].

The DSTACOM/NAS system implements three modes of operation, i.e. voltage control, power factor correction and active power control. The integrated DSTATCOM plus energy storage system is basically composed of the inverter, a coupling step-up transformer, a line connection filter, dc bus capacitors, and the array of batteries [12].

The inverter corresponds to a dc to ac switching power inverter using Insulated Gate Bipolar Transistors (IGBT). The output voltage control of the DSTATCOM can be achieved through pulse width modulation (PWM) by using high-power fast-switched IGBTs.

The connection to the utility grid is made by using low pass sine wave filters in order to reduce the perturbation on the distribution system from high-frequency switching harmonics generated by PWM control.

The multi-level control scheme for the integrated DSTATCOM/NAS device, consisting of an external, middle and internal level, is based on concepts of instantaneous power on the synchronous-rotating dq reference frame [13].

The external level control is responsible for determining the active and reactive power exchange between the enhanced custom power device and the utility system. The external level control scheme is designed for performing three major control objectives, that is the voltage control mode (VCM), the power factor control mode (PFCM), and the active power control mode (APCM) that is always activated.

- **The middle level control** makes the expected output to dynamically track the reference values set by the external level.
- **The internal level** is responsible for generating the switching signals for the twelve valves of the three-level inverter, according to the control mode (sinusoidal PWM) and types of valves (IGBTs) used.

NAS model tested in a microgrid

The MG used to validate the proposed model is depicted in Figure 8 as a single-line diagram. Such a system implements a 100 MVA substation represented by a Thevenin equivalent, which feeds a distribution network operating at 25 kV/50Hz. The loads are modelled by constant impedances and are grouped together at bus 3. A 20 km distribution line modelled with parameters lumped in PI sections links the loads to the substation. The DSTATCOM/NAS device is connected at bus 3.

This compensator includes a 25/2.4 kV Yg/Δ step-up transformer and a ±2 Mvar inverter coupled with a 1.5 MW set of NAS batteries.

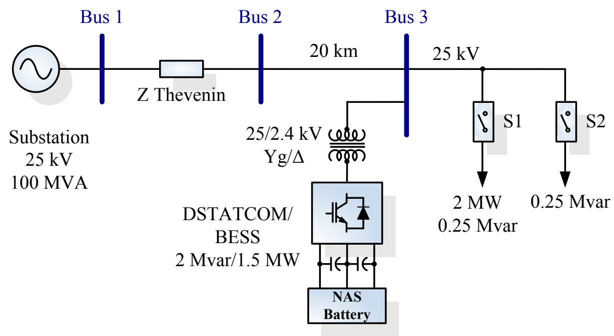

Figure 8: Single-line diagram of the microgrid test system with DSTACOM/NAS system

Performance of the models and control schemes is analyzed by computer simulation performed in SimPowerSystems of SIMULINK/MATLAB™ [10]. A variable load is connected at bus 3 and is changed during the simulation in order to verify the dynamic response of the proposed compensator/battery system.

The topology presented in the test system is first tested without the connection of the DSTATCOM/NAS device. Under this scenario, the distribution utility feeds a group of 2 MW/0.5 Mvar variable loads. The supply voltages and currents are balanced and in steady state. Then at t= 2 s, a set of loads equivalent to 0.215 Mvar are automatically connected and disconnected at t= 4 s at bus 3. The inductive reactive load produces a decrease of the terminal voltage at bus 3.

The impact of the inclusion of a DSTATCOM/NAS controller at bus 3 operating in PFCM can be analyzed from t= 3 s. At t= 3 s the DSTATCOM/NAS provides reactive power for improving the power factor and also the voltage profile. In this way the reactive power demanded from the electric grid at the point of common coupling (PCC) changes from 0.5 Mvar to almost null. The active power demand is also reduced due to the contribution of the NAS battery.

With the inclusion of the DSTATCOM/NAS in PFCM mode, the main goal of the compensator is to maintain a unity power factor. As can be derived from Figure 9, at t= 3 s begins the compensation of reactive power that rapidly provides a unity power factor independent of loads variations. In these conditions, the terminal voltage level at PCC is also enhanced although at a smaller level that in VCM mode.

At t= 4 s, the device changes from injecting power to absorbing power from the grid. In such situation, the battery set changes from discharging to charging mode.

Figure 9 presents the response of the system before, during and after the contingency described.

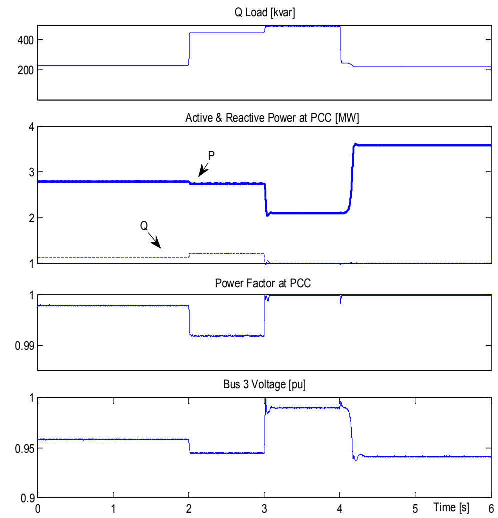

Figure: Simulation of the DSTATCOM/NAS system in a micro grid.

Conclusion

The sodium–sulphur battery presents interesting opportunities for energy storage in power systems. The sodium-sulphur batteries are much smaller and lighter than other classical batteries and they have neither memory effects nor toxic materials. Disadvantages of sodium batteries are few when considering them for energy storage. To date, the main obstacles for the large scale applications of sodium-sulphur batteries are found on their high production costs which depend greatly on the scale of battery production. The most important obstacle, however, is the lack of an electrical model that simulates its dynamic behaviour.

In this paper the authors have developed a new NAS model suitable to study the insertion of NAS batteries modules into microgrids systems. Dynamic system simulation studies demonstrate the effectiveness of the developed NAS for a single cell and in a microgrid system. More tests and adjustments should be carried out to demonstrate its performance in large power systems and also to check their long-term dynamic behaviour.

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(Endnotes)

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