PRICE-BASED CONTROL STRATEGIES FOR ELECTRIC ENERGY STORAGE SYSTEM IN DISTRIBUTION NETWORKS

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ABSTRACT

This paper presents and evaluates different control strategies for a vanadium redox flow battery energy storage system (VRB). EDP HC Energía, and other partners through the REDOX 2015 research and development project have built a vanadium redox flow battery prototype. This prototype is integrated in the distribution network belonging to the utility to prove its operation as demand balancing tool. Besides, a simulation model is needed in order to conceive and design different control strategies for the following implementation and operation of the prototype. A comparative study is thereby carried out to analyse the impact of the control strategies developed in the charging/discharging patterns and state of charge of the battery. The simulation results show that the control strategies developed can achieve an excellent performance as demand support tool and can lead to efficient energy usage, reducing the end user cost of energy and decreasing the distribution networks equipment stress.

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INTRODUCTION

There were two main objectives in REDOX 2015 project: to develop a VRB by Spanish partners and to increase knowledge in new components for the next generation of VRFB. The project consortium was made by EDP Spain, ZIGOR, ISASTUR , University of Oviedo, TECNALIA, IREC, INCAR and TEKNIKER [1]. Once the prototype was developed, EDP Spain has carried out a study to find the best location in its grid to perform the tests of the system according to the battery size and other constraints. The selected location was near a HV/LV substation called Pumarin in Gijón (northwest Spain) and connected to the LV grid through a small MV/LV substation in order to feed a building from EDPs offices (Figure 1).

Regarding the energy storage system model, it is developed in Digsilent Power Factory software. In order to improve the model reliability, not only does it consider the voltage source model, the converter and the connection transformer but also the detailed electrochemical relationships among the battery stack magnitudes, the pump operation and the state of charge (SOC) to determine the voltage between the battery terminals and the charge controller behaviour.

Figure 1. VRB Prototype location

Transformer protection to limit the apparent power flowing through the MV/LV transformers, peak shaving to limit the active power consumed by the loads, and price mode that determines the optimum times to charge or discharge the battery according to the real time end users electricity prices have been implemented in the control model. These three control methodologies have been tested and validated through simulations for different operational scenarios by means of Digsilent Power Factory software.

BATTERY MODEL

In order to implement the simulation model of the VRB battery, the equivalent circuit explained in [2] and shown in Figure 2 has been employed.

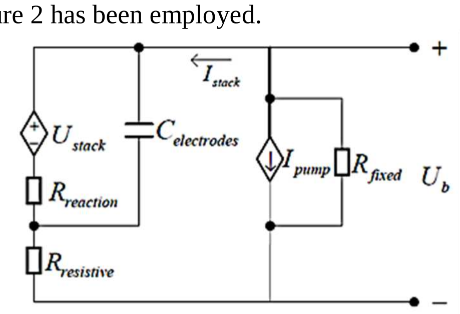

Figure 2. VRB equivalent circuit.

Digsilent battery model is made up by a direct current voltage source controlled through an algorithm based on the dynamics equations that model the behaviour of the equivalent circuit used. Every control scheme and formula have been implemented through DSL-Frames (Digsilent Simulation Language). As an example, Figure 3 depicts the frame used to obtain the current value in the battery cells as a function of the current terminal.

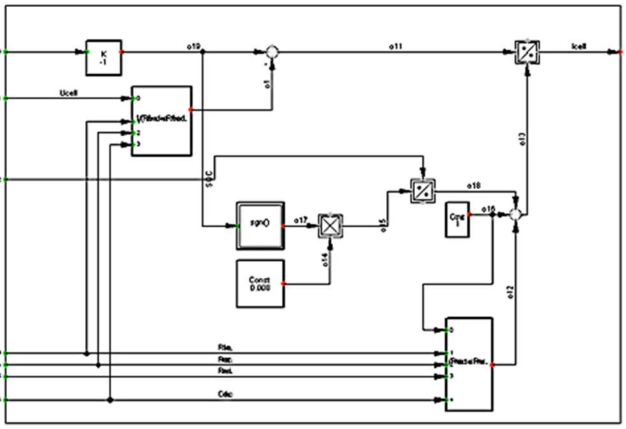

Figure 3. Icell Frame

Control model

The control system DSL-frame is based on ten slots that are represented in Figure 4. A description of every slot is provided in the following paragraph.

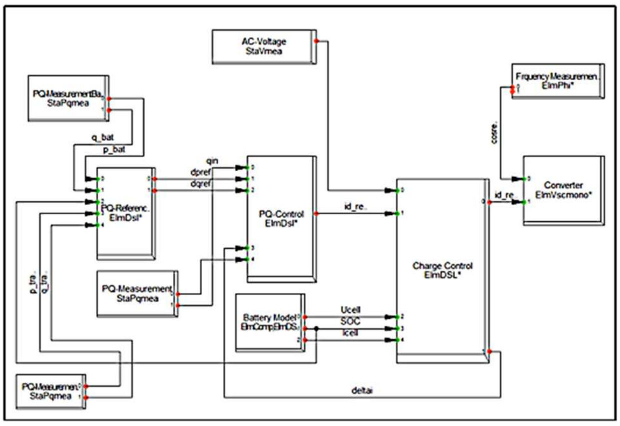

Figure 4. Overall VRB model

Voltage measurement: it measures the ac voltage in the terminal to be controlled, in order to determine the reactive power needed.
Frequency measurement: it measures the value of the cosα y sinα to allow the dq coordinate transformation. **PQ Battery measurement**: it measures the active and reactive power delivered by the storage system.
PQ transformer measurement: it measures the active and reactive power delivered by the transformer.
Battery model: contains the DSL frame of the battery model explained in Figure 2. It informs the charge controller about the charge level of the battery.
Converter: holds the converter that is to be controlled.
P-Q Control: the control diagram that calculates the dq components of current the converter needs to supply the active and reactive power references that must be calculated previously.
Charge Control: this control modelled through a DSL-frame aim to control all the constraints that have to be observed, such as the battery charge level, the maximum current or the priority between the active and reactive power.
P-Q Reference: this slot is conceived in order to calculate all the references needed to control de battery regarding the control mode chosen and the grid measurements. For this purpose, Isastur proposed model have been implemented. This model is explained in the control strategies section.

CONTROL STRATEGIES

The storage prototype was designed to be connected to the LV grid, to prove its operation as demand balancing tool. In order to support different storage management strategies, the model includes a Demand Balance Controller, specifically designed to optimize usage of the storage system and integrate it within grid operation. The Demand Balance Controller is connected with different measurement units in order to receive actual grid values and main storage parameters, as well as to send power set points to the battery management system.

The strategies implemented in the Demand Balance Controller are: **Transformer protection mode**, in order to limit the apparent power flowing through the ML/LV transformers. **Peak shaving mode**, in order to limit active power consumed by the loads. **Price mode strategies**. Real time bill optimization following either price signals or flat rates (two different options).

In order to develop these three strategies, the control method deals with 11 parameters and 19 variables shown in tables 1 and 2.

Table 1. Strategy control parameters.

Parameter	**Description**
P_{MAX}	Maximum power removable from the battery.
ΔP	Minimum variation step of the delivered/absobed power when it is required a soft variation.
ActivFactorPrecio	Indicates whether to use the price dependent factor (Fprecio) sent by SCADA.
Sv	Factor to soften the possible sudden changes when references according to the price are used instead of the load transformer.
Max_{SOE}	Maximum battery charge level allowed.
Min_{SOE}	Minimum battery charge level allowed.
SUP_{SOE}	Above SOE value to start lessening the charge references of the battery
INF_{SOE}	Below SOE value to start lessening the discharge references of the battery
OPT_{SOE}	Optimum charge level of the battery. It is desired to achieved when the transformer is within acceptable levels of active power delivery.

ΔSOE	Band around the $OPT_{SOE.}$ To avoid oscillations around OPT_{SOE} when the power delivered is closed to 0, we consider a band of optimum values instead of one value.
DELAY	Waiting time for the references and feedback to stabilise

Table 2. Strategy control variables.

VARIABLE	ORIGIN	DESCRIPTION
PT_r	Trafo>=RTU	Active power delivered by the transformer r phase
PT_s	Trafo>=RTU	idem s phase
PT_t	Trafo>=RTU	idem t phase
QT_r	Trafo>=RTU	Reactive power delivered by the transformer r phase
QT_s	Trafo>=RTU	idem s phase
QT_t	Trafo>=RTU	idem t phase
PB	Battery>=RTU	Active power delivered/absorbed by the battery
QB	Battery>=RTU	Reactive power delivered/absorbed by the battery
SOE	Battery>=RTU	State of charge of the battery (State Of Energy)
ND	SCADA	Discharge level. Transformer active power flow above the battery should deliver active power
NC	SCADA	Charge level. Transformer active power flow below the battery should absorb active power
FPrecio	SCADA	Price factor. Maximum power, expressed in per unit, the battery can deliver (P_{MAX}) required by the SCADA to be delivered/absorbed according to the hourly price of energy.
VARIABLE	**DESTINATION**	**DESCRIPTION**
PC	Trafo>=RTU	Active power reference for r phase
QC	Trafo>=RTU	Reactive power reference t phase
VARIABLE	**DESCRIPTION**	
PT	Sum of the active power delivered by the transformer	
QT	Sum of the reactive power delivered by the transformer	
FD	Discharge factor. Factor to multiply to the theoretical reference to lessen it according to the charge level (if applied) or to cancel it if the battery is more discharged than the allowable	
FC	Charge factor. Factor to multiply to the theoretical reference to lessen it according to the charge level (if applied) or to cancel it if the battery is more charged than the allowable	
P_{Libre}	Surplus power for the reactive control	

In order to determine the active and reactive power references , we need to consider the power flowing along the transformer that feeds the load through the distribution network (PT control variable). This will give three possible results. On the one hand, if the power circulating along the transformer is greater than the previoulsy designed discharge level (ND), the battery will be responsible of supplying that surplus of power, therefore the battery will discharge. But, on the other hand, if the power along the transformer is greater than the previoulsy designed charge level (NC), the battery will be responsible of absorbing that deficit of power, therefore the battery will charge. Finally, when the power along the transformer is within NC and ND levels, two control modes (A and B) have been implemented.

Regardless the control mode selected, once the power reference PC is obtained, it needs to be recalculated in order to consider the battery charge levels provided by the FC and FD factor. The control behaviour ensures that the closer the battery is to the charge limits, the lower is the power reference as can be deduced from the expressions used in the algorithm

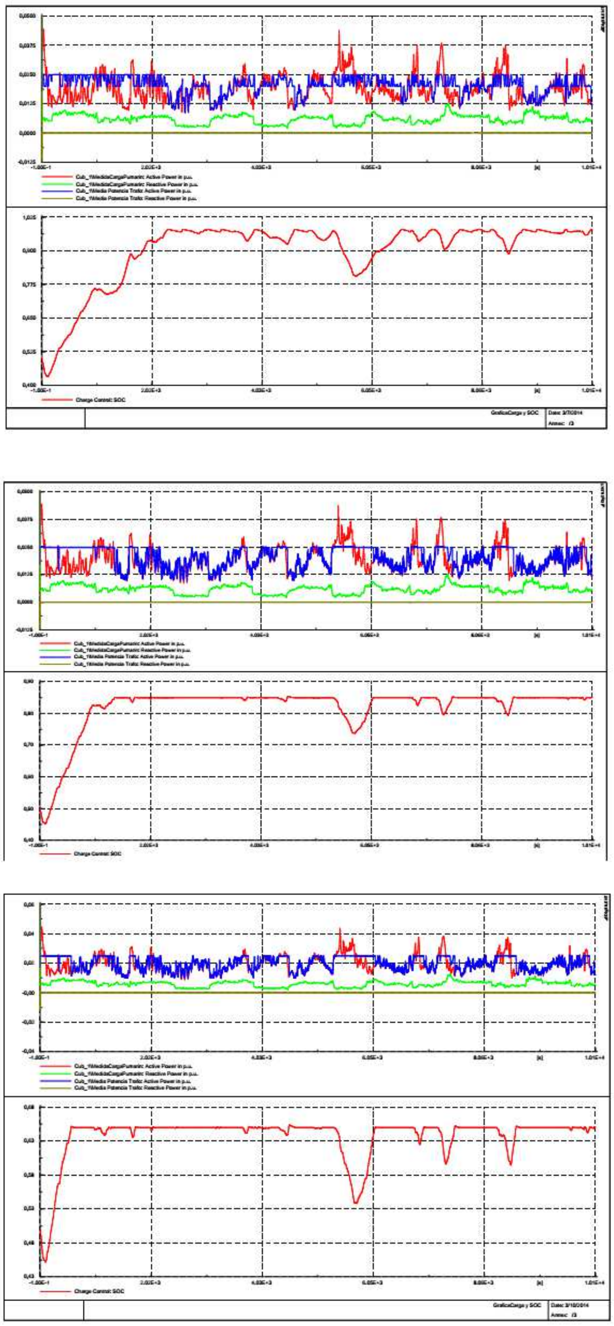

Fig 1Results for modelling of one control mode with different parameter values

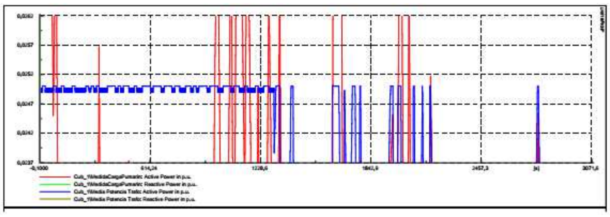

Fig 2 Fluctuating behavoiur appears at a closer look using different time frame.

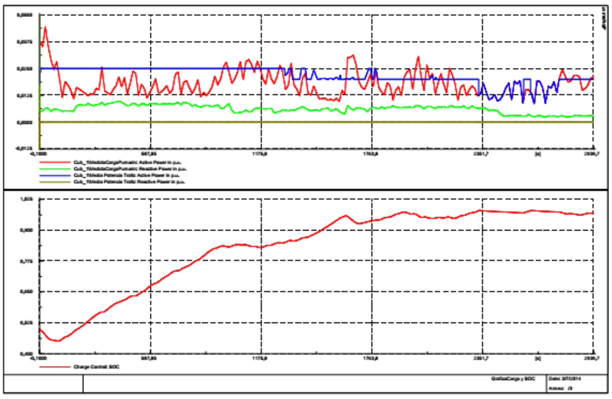

Fig 3Behaviour at maximun SOC

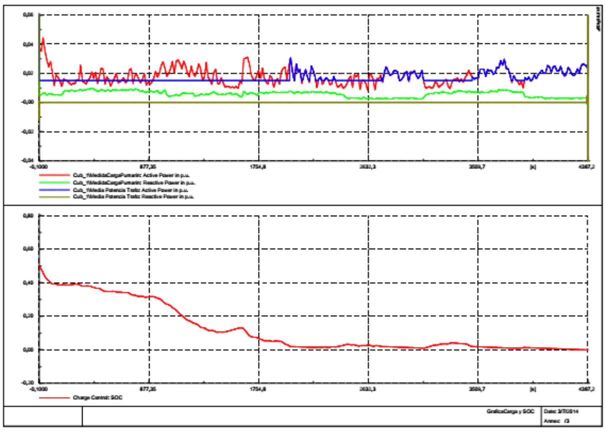

Fig 4Behaviour at minimum SOC

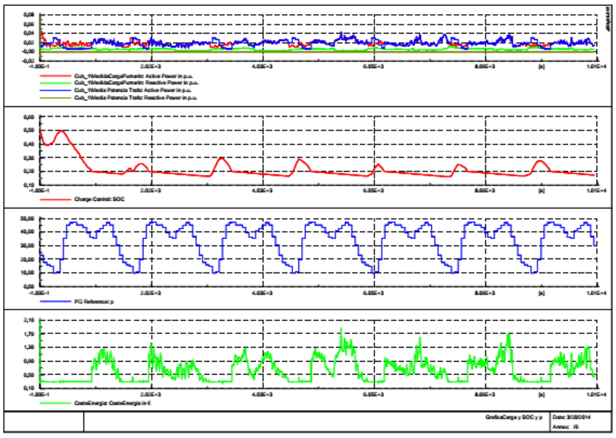

Fig 5 Modelling result for a strategy taking into accout price signals

CONCLUSIONS

Several simulation studies have been developed considering various scenarios defined by different grid conditions and varying the control parameters. The simulation results show that the control strategies developed can achieve an excellent performance as demand support tool and can lead to efficient energy usage, reducing the end user cost of energy and decreasing the distribution networks equipment stress. The validation of the control algorithm is currently in a demonstration stage using the prototype that is already installed.

REFERENCES

[1] L. Santos, R. Ferrer et al. “Developing a redox flow battery with spanish Technology. Project REDOX2015”. *23rd International Conference on Electricity Distribution, CIRED 2015, paper 0750.*

[2] Chen, Z., Ding, M., & Su, J. “Modeling and control for large capacity battery energy storage system”. 2011. *4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT).*

[3] Chahwan, J., Abbey, C., &Joos, G. VRB “Modelling for the Study of Output Terminal Voltages, Internal Losses and Performance”. *2007 IEEE Canada Electrical Power Conference,*

[4] Barote, L., Marinescu, C., & Georgescu, M. “VRB modeling for storage in stand-alone wind energy systems”. *2009 IEEE Bucharest PowerTech*.

[5] Wang, W., Ge, B., Bi, D., & Sun, D. “Grid-connected wind farm power control using VRB-based energy storage system”. *2010 IEEE Energy Conversion Congress and Exposition*.