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Proyecto 14-INV-271
“Valuación de Inversiones en Infraestructura Eléctrica y Comportamiento Estratégico”

ANEXO 07
PGT 2.1 – Formulación matemática de modelos de Opciones Reales – Informe

Analyzing energy storage system for energy arbitrage

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Abstract— **The need for integration of renewable energy to the electricity grid promotes research and development of new energy storage technologies, as well as models and techniques to study them. In this sense, the present work proposes a model to evaluate the benefit that can be harnessed through energy arbitrage in function of a daily hourly rate differentiation. The Vanadium Redox Battery is one of the energy storage technologies that have proven most interesting for stationary applications in recent years, especially to medium and large-scale installations. A mathematical model is presented and applied to a case study to evaluate the feasibility of investing in an energy storage system of vanadium redox batteries. The results indicate that at present the capital cost should decrease around 75% to be considered profitable for the case study. Finally, real options approach analysis is suggested to assess the flexibility offered by VRB ESS, such as relocation, expansion and abandonment.**

Keywords— Energy arbitrage, Energy storage, Vanadium Redox Battery.

I. INTRODUCTION

Several scientific studies, market tendencies, political actions, among others, show that energetic transition and sustainable development towards a cleaner matrix based on the integration of renewable energy resources, electric vehicles, distributed generation, smart grids, are no longer “things from the future”, they are being real [1]. In this reality, Energy Storage Systems (ESS) are of fundamental importance, with applications in every electric energy supply chain [1]- [2]- [3].

Historically, energy supply systems planning was built on generation control, bearing in mind the uncertain demand, variable and impossible to predict with accuracy. However, in recent times this planning mechanism is becoming obsolete. This is due to intermittent renewables introducing uncertainty in energy generation. Also, the increment of control and automation technologies from the demand’s side, jointed with a growing awareness about the need of energy efficiency worldwide, creates a necessity to storage energy [4].

In this context of paradigms shift in expansion planning of energy systems, the ESS are gaining each time more space, not only within isolated appliances but also in energy storage for the grid, thanks to its operational malleability and the adaptability that they offer at the moment of integrating intermittent generation and programmed demand, thus becoming an important link for the planning of new expansions in the electrical system [5].

Energy Arbitrage implies the purchase of low cost energy when available during periods of low-demand to charge the storage plants, therefore being able to use or sell the energy when the price is convenient [6].

During the last few years, ESS technological advancements has brought uncountable benefits as well as large amounts of new challenges. The effort to determine models that can be applied to stablish the real benefit of this ESS is translated into large number of scientific articles boarding different aspects of these systems. In this path, our present work aims to evaluate the isolated benefit that can be exploited through Energy Arbitrage in function of a daily hourly rate differentiation.

II. VANADIUM REDOX BATTERIES

Energy density is a characteristic with increasingly importance for mobile applications, however, within stationary appliances, this property loses hierarchy at the moment of deciding for an appropriate technology to be used [5].

Lithium-Ion battery, like Tesla’s Powerwall, is leading the market of small facilities and mobile applications, but, from thorough analysis of technical literature, we found evidence that alternatives, like Redox-based technologies, can be more suitable for medium and large-scale applications [7]- [8].

Flow batteries are those in which the electrolyte circulates through battery cells (where the electrodes are contained) and is being pumped from storage tanks [7]. External tanks can be utilized for electrolyte storage. This important characteristic allows to design custom batteries, where the storage capacity of the energy system is defined by the size of the tank, whereas the nominal power depends on the number of combined cells in series (stack).

Vanadium Redox Battery (VRB), is one of the energy storage technologies that has shown to be the most interesting for stationary applications in the last few years. It owns a high-capacity of charge/discharge response, allows the design of energy capacity and independent power, and self-discharge loses are relatively low [6]. Currently, installed megawatt-scale (MW) systems exists in the United States and Europe (2MW/8MWh, 4MW/6MWh) while the largest system of the world is located in China with 5MW/10MWh, where in 2020 at Dalian, an ESS based on VRB with the capacity of 200MW/800MWh is expected to be inaugurated, according to announcements from China’s National Energy Administration [9].

The main advantages of the VRB against Lithium-Ion batteries are el long cycle life superior to 10.000 cycles against 1.000 from Li-Ion, besides they are non-flammable, and the cost in relation to the storage capacity decreases as the size of the electrolyte tank increases [10]. In references [7] shows that charge/discharge efficiency increases as the related power increases too. However, the state of charge (SOC) does not affect efficiency, this facilitates the mathematical modeling for the possibility of assuming a constant efficiency.

III. MATHEMATICAL MODEL

In [11] are presented a review of previous mathematical models published up to the present in the search of one that represents the behavior of the VRBs and its benefits faithfully, but wasn't possible to found any complete model, rather isolated parts of different perspectives.

A. Hypotheses

Due to the complexity of fully modeling the ESS, we have adopted certain simplifying hypotheses, as a way to distinguish the possible benefit of energy arbitrage in function of a daily hourly rate differentiation. Future papers may delve the totality of benefits of the use of ESS VRB.

1. There is a difference of Price between on-peak and off-peak periods.
2. ESS are capable of charging fully at off-peak times and discharge fully at on-peak times.
3. ESS would perform according to a stablished schedule, not as an emergency backup. We assume this characteristic of the modeling to show the evidence of economic revenue obtained exclusively through energy arbitrage.
4. The generators in model are considered as traditional thermoelectric generators.

B. ESS ecuations

According to adopted hypotheses, ESS would be loading daily until they reach maximum storage capacity, allowing to inject the available power to the grid at maximum discharge power ESS_d.

Although with ESS VRB, storage capacity is dimentionable independently to its power capacity, it is not advisable to exceed energy storage that will be able to inject during peak periods t_p, because the main objective is to maximize benefit in function of energy arbitrage. For this reason, the storage capacity ESS_{max} is a function of maximum discharge power ESS_d and the efficiency η between charge and discharge.

$$ESS_{max} = \eta * ESS_d * t_p \tag{1}$$

Efficiency is given by the relation between the amount of energy injection ESS is capable of discharge during peak hours and the amount of energy loads that the ESS must buy in low-demand hours

$$\eta = \frac{Wh\ discharge}{Wh\ charge} \tag{2}$$

The state of charge (SOC) of the battery can also be represented by the depth of discharge ρ. There is a minimum amount of energy that the battery must maintain to assure correct performance. The relationship between minimum amount of energy ESS_{min} and storage capacity ESS_{max} in function of depth of maximum discharge ρ_{max} is shown in equation 3. Some VRB manufacturers assure that their products can get to a Depth of discharge up to 100% and remain discharged for long periods of time without affecting the ESS efficiency negatively.

$$ESS_{min} = (1 - \rho_{max}) * ESS_{max} \tag{3}$$

Daily charging power required by the ESS during low-demand hours would be the difference between ESS_{max} and ESS_{min} during the time t_b of low-demand periods.

$$ESS_c = \frac{ESS_{max} - ESS_{min}}{t_b} = \frac{\rho_{max} * E_{max}}{t_b} \tag{4}$$

C. Stochastic Simulation

Electrical Market uncertainty can be simulated using the Monte Carlo method, modeling the main variables through adequate stochastic processes.

When planning expansion systems for ESS it is fundamental to know the demands growth. In previous studies similar to our work it is common to find stochastic models of the demand growth, represented by a generalized Brownian motion according to the following expression in equation 5:

$$dTc(t) = \mu_{d_i}.dt + \sigma_{d_i}.dz \tag{5}$$

due mainly to the inelasticity of demand in relation to energy price. Where dTc_i is the demand's growth rate in the interval of dt, μ_{d_i} is the average growth rate estimated for the year t. $\sigma_{d_i}^2$ is the estimated variance for the period of time and dz is the variation of z variable in the Weiner process.

On the other hand, the uncertainty in the generation cost of thermal power stations is strongly linked to the price fluctuation of the fuel being consumed by these plants. For cases like this, an appropriate way of representing the uncertainty of fuel prices is through the mean-reverting stochastic process, shown in equation 6.

$$dp_F(t) = \alpha\left(\overline{p_F} - p_F(t)\right) + \sigma^{p^F}.dW \tag{6}$$

Where α is the velocity of mean-reversion, σ^{p^F} is the price volatility of fuels used by the thermal power stations and $\overline{p_F}$ is the average price of fuels p_F.

D. Financial analysis

R incomes that can be obtained by the means of energy arbitrage using ESS VRB can be calculated as the difference between energy sales income I_s in on-peak hours and energy purchase costs in off-peak hours C_{buy}, also bearing in mind the operational and maintenance costs C_{opm}, like shown in eq. 7.

$$R = I_s - C_{buy} - C_{opm} \tag{7}$$

To determine if an investment is profitable, it is common to calculate the Net Present Value (NPV) taking in to account a discount rate *r* and the income *R* for each year *i* during *n* years of the horizon analysis and the initial investment capital C_{inv} as shown in equation 8.

$$NVP = \sum_i^n \frac{R_i}{(1+r)^i} - C_{inv} \tag{8}$$

Currently in the literature we found information about ESS VRB that are being able to stand over 10.000 cycles of charge/discharge for 20 years without affecting the efficiency or storage capacity [2][4]. However, this kind of long-term projections carry great uncertainty both in the energy market as in technology market, as well as external factors that may affect the planning process. For this work, we have adopted a period of time of 10 years.

E. Study case

The selected system shown in Fig 1 count with thermal generators in each one of the three nodes, in addition to the demand on each one of them. ESS could be set up on any of the three buses, or even on several. As a project decision, we assume that ESS will be installed on the bar with least nodal Price of energy in low-demand periods, in this case is node 1.

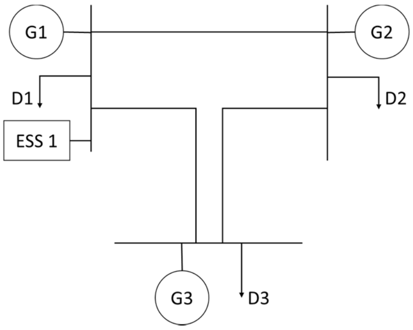

Fig. 1. Study case system

For the annual analysis, the year is divided in 4 periods representing the seasons with differentiated loads, and observed that summer and winter had the highest demand. For each season, a typical day is modeled in hours of low, medium and peak demand on each node. From a base demand listed in Table I, considering a growth rate of 2% and standard deviation of 0.5%, through Monte Carlo simulation stochastic demand can be obtained.

Table II indicates the data about capacity from the generators installed on each bar, as well as base coefficient related to fuel costs for power generation. Considering a mean-reversion factor of 65% with a growth rate deviation of the cost of 16.7%.

The wide variety of information about the cost of VRB technology makes it difficult to determine the real cost for VRB systems. Reference [10] developed detailed analysis of cost and reference [12] made an update, esteeming the annualized cost around $24,000/MW and operational cost stipulated $1.6/MWh. For the chosen capacity, initial investment of $13,746,000 is calculated with a discount rate of 10%, in addition to yearly maintenance and operational cost of $29,200.

IV. RESULTS

According to distribution density on Fig 2, expected NPV is around -10,3 million of dollars with a standard deviation of approximately $166.000. Concluding that investment is not profitable with the current investment cost In Fig 3 a sensitivity analysis it's performed by reducing investment cost for ESS VRB technology between 70 and 80%.

TABLE I. BASE LOAD

LOAD				
Season	Bus	Low [MW]	Medium [MW]	Peak [MW]
Spring and Autumn	1	75	100	130
	2	100	150	190
	3	150	200	290
Summer	1	140	170	215
	2	190	230	280
	3	220	300	410
Winter	1	115	150	200
	2	160	195	245
	3	195	250	360

TABLE II. GENERATION DATA

GENERATION				
Bus	Pmax [MW]	Quadratic Cost [$/MW]	Linear Cost [$/MW]	Fixed Cost [$/MW]
1	500	0,01	10	180
2	200	0,02	20	120
3	400	0,055	55	270

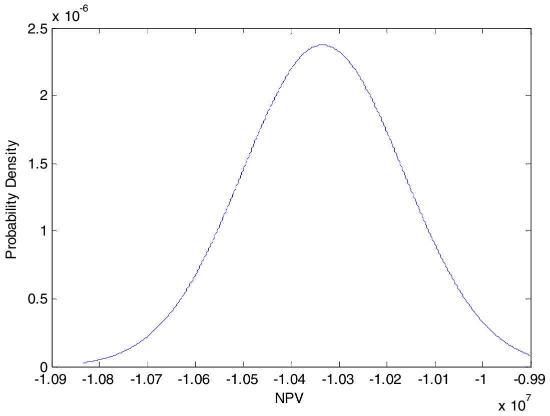

Fig. 2. NPV Probability Density

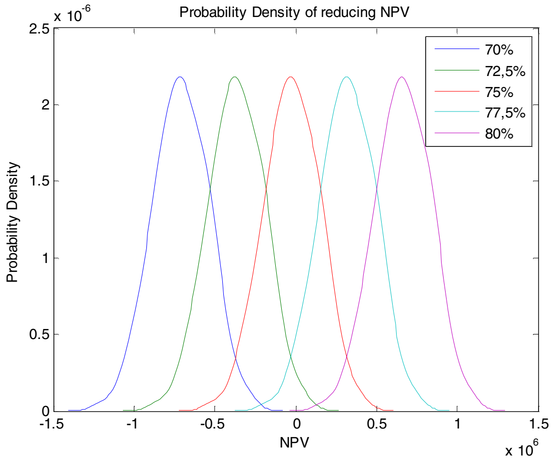

Fig. 3. Cost Sensitivity Analysis

The cost reduction with the relating accumulated probability density can be drawn as in Fig 4, where it can be observed that to obtain 50% probability of positive NPV, i.e., a normal probability density distribution with a means in cero, we need a 75.5% reduction.

Apparently, there is still a long road ahead to go for ESS VRB under the traditional financial analysis. But if the additional flexibility given from this technology to the system could be valued, vanadium batteries could be attractive for the performance of the grid. A good technique that may be harnessed for this purpose would be the Real Options analysis.

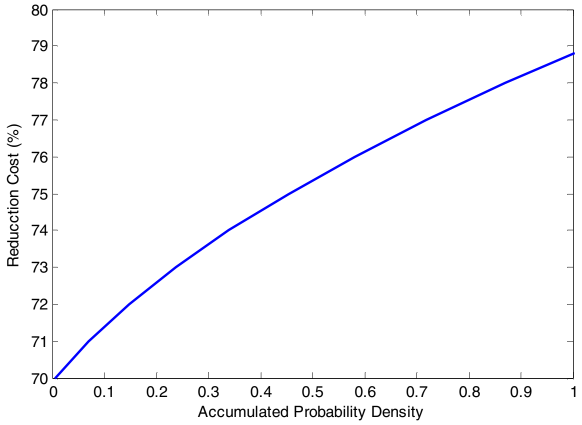

Fig. 4. Accumulated Probability Density

V. CONCLUSIONS

Paradigms shift in the planning of electric systems is irreversible. Renewables and storage systems bear a fundamental role. For medium and large-scale applications, certain advantages exist, like independent sizing of energy and power, better scalability, large depth of discharge, prolonged life cycles, among others.

A mathematical model has been presented which analyses the benefit from daily energy arbitrage in function of the price difference between on-peak and off-peak demand periods.

Currently and under traditional financial analysis, Vanadium Redox Batteries should have reduced costs of investment at least 75% to get at around 50% of probability to be considered profitable, i.e., to achieve a positive NPV.

On the other hand, ESS add operational flexibility to the system and for future investments. Evaluations of the value of flexibility can be made with Real Options technique and the conclusion might be propitious for the ESS.

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