Cycle Charging Strategy for Optimal Management of Vanadium Redox Flow Batteries Connected to Isolated Systems

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***Abstract*—Large-scale integration of renewable resources for power generation is a propitious mode to mitigate the impact of human activities in order to reach an environmentally and sustainable way of life. However, uncontrollability and variability of renewable resources is an important barrier that could be overcome by incorporating energy storage systems (ESSs). Among ESSs technologies, Vanadium Redox Battery (VRB) is a promising technology able to be incorporated in isolated and insular power systems with limited geographical conditions and high natural resources, thus increasing the system framework flexibility. Under this context, development of a proper strategy to control VRB in daily scheduling of insular systems, considering charge controller operation and VRB dynamic behavior, is a necessity. Hence, this paper presents an optimization model based on cycle charging strategy capable to include these features. The proposed approach is illustrated by analyzing two systems, obtaining a reduction on generating costs between 1.35% and 25.3% depending on system characteristics, wind power profile, and its penetration level.**

***Index Terms*—Economic dispatch, energy storage system, unit commitment, vanadium redox battery, wind power**

I. INTRODUCTION

The increasing installation of renewable power generation required to mitigate the effects of human activities related to greenhouse gas emissions and required to develop an economically sustainable energy system is limited by several technical characteristics related to the variability and unpredictability of these types of sources. Efficient operation of power systems provided of renewable generation such as wind and solar power is carried out by using predicted values of renewable generation; however, the intrinsic error of such predictions make difficult the operation of the system under optimal conditions. To solve this problem, in many places around world has been implemented the installation of energy storage systems (ESSs) in order to improve the flexibility of the system, incrementing the penetration level of renewable generation as well as its accommodation. Under this context, several mathematical techniques to determine the optimal scheduling of thermal generators, renewable generation, and power dispatch of ESS have been developed.

In [1], a methodology to solve security-constrained unit commitment (SCUC) able to consider the effects of ESSs and wind generation was proposed. The same approach was designed to consider compressed air energy storage (CAES) system and technical constraints of thermal generating units as well as fuel and emission limits. Additionally, the influence of CAES system on peak-load shaving, and wind power curtailment were analyzed. In [2], the stochastic version of SCUC incorporating pumped-hydro storage (PHS) generation has been proposed to optimize the hourly coordination between PHS and wind generation. This stochastic approach was based on scenario generation/reduction method using an autoregressive moving average (ARMA) model, while the scheduling is formulated as a mixed integer problem (MIP) efficiently solved by using Benders' decomposition technique. In [3], a scheduling problem considering wind power and PHS generation has been solved by using robust optimization approach at which, random variables are modeled by including the worst-case scenario so that the obtained solution was provided of high reliability; however, with a high operating cost. In order to face this problem, control variables were incorporated to manage the conservatism of the solution, avoiding the cost related to over-protection. In [4], a general purposes ESS model was developed which was able to be incorporated in scheduling problems solved by mixed-integer linear programming (MILP) formulation.

As can be noted, many of the models presented in the technical literature have been designed for systems provided of PHS systems, which requires several specific geographical characteristics that cannot be found in all insular systems. Vanadium Redox batteries (VRBs) could be a good alternative for multi-megawatts ESSs; however, there are several technical characteristics related to the charge controller operation that cannot be modeled by means of a linear formulation.

In our previous work [5], the scheduling problem considering VRBs was analyzed by using load following strategy at which, wind power curtailed is used to be stored on ESS in order to level the load profile to be supplied by thermal generators.

Under this strategy, cost saving and improvements on wind power accommodation could be limited by the wind resource availability. To overcome this problem, in this work is introduced a cycle charging strategy on scheduling problem at which, part-loaded units are used to generate energy that is stored on ESS and therefore, the energy provided by cheapest thermal generators could be used for load leveling, in order to reduce power supplied by the most expensive generators typically used for providing energy during peak-loads.

II. ENERGY SYSTEM MODELING

A. *Conventional and Renewable Generation*

Frequently, thermal generators are modeled by means of a quadratic expression which represents the relationship between the output power and the cost related to the fuel required to provide such power. In this paper, a linear approximation has been used [6]; besides of this, other technical limitations related to the ramping capabilities, minimum up and down time constraints, and minimum and maximum output power have been considered. Regarding load demand and wind generation; these have been modeled by means of the corresponding predictions in daily basis. Load demand could be forecasted by using an ARMA model or an artificial neural network, while wind generation could be predicted through numerical weather prediction method [7].

B. *Battery Energy Storage System*

As stated before, BESS considered in this paper are based on VRB. To represent dynamic behavior of this storage technology, several models have been recently proposed in the literature. In [8] was developed a VRB model able to describe state-of-charge (SOC) and battery voltage based on an internal potential source that depends on SOC, internal resistance, and a constant auxiliary power equals to 10% of the BESS rated power. However, other characteristics such as pump operation are not incorporated in order to reduce the mathematical complexity of the model enough to evaluate the economic role of BESS to provide frequency regulation services.

In [9], experimental experiences obtained from charging and discharging cycles considering several SOC values between 0.2 and 0.75 were used to build a simulation model able to include the relationship between the overall system efficiency and SOC through the estimation of energy losses at stacks from electrochemical conversion and auxiliary power consumption. The model presented in [10] puts special attention on representing power consumption of auxiliary systems. Besides of other important features of VRB previously mentioned; the same model is used in this paper for optimal scheduling of insular systems.

Fig. 1 shows the simplified circuit model of battery, where $V_{B,t}$ is the battery voltage, $I_{B,t}$ is the battery current, $I_{P,t}$ is the battery pump current, $V_{S,t}$ is the battery stack voltage, $I_{S,t}$ is the stack current at time t, while R_S is the equivalent resistance of the battery.

$V_{S,t}$ is related to SOC at time t (SOC_t) through a linear relation ($f(SOC_t)$) proportional to the open circuit voltage (E_t) according to (1):

$$f(SOC_t) \propto E_t \tag{1}$$

where E_t is defined according with (2):

$$E_t = \gamma + \delta(SOC_t) \tag{2}$$

where parameters γ and δ can be experimentally determined. The number of cells of VRB is the proportionality constant between the variables E_t and $V_{S,t}$. Power loss related to the auxiliary systems is represented by $I_{P,t}$ which depends on SOC and stack current through the function (3):

$$I_{P,t} = f(SOC_t, I_{S,t}) \tag{3}$$

which is experimentally measured. Fig. 2 shows an example of this relationship obtained by scaling the information presented in [10]. For a specific operating condition, values of SOC and stack current are evaluated in Fig. 2 by means of a linear interpolation to estimate the corresponding pump current.

Then, from the analysis of circuit presented in Fig. 1 for this condition, any variable of interest could be properly calculated. Charge controller is a key element to the correct operation of VRB, its effect has been incorporated in the estimation of SOC through the factor F_t. SOC at any time t can be estimated by using (4):

$$SOC_t = SOC_{t-1} + \frac{P_{C,t}^{r} \Delta t}{E_B^{max}} F_t \tag{4}$$

where $P_{C,t}^{r}$ is the reference of charging power, Δt is the time step, E_B^{max} is the rated energy of the battery, and F_t is the control factor at time t. F_t is calculated by means of (5) [5]:

$$F_t = \begin{cases} max\left(1 - e^{\left[\left(\frac{\alpha}{\frac{P_{C,t}^{r}}{P_B^{max}} + \beta}\right)(SOC_t - SOC_{max})\right]}, 0\right); & P_{C,t}^{r} > 0 \\ 1; \; P_{C,t}^{r} < 0 \end{cases} \tag{5}$$

where P_B^{max} is the rated power of VRB. This factor is used to represent the reduction on the power effectively stored in the battery when SOC is reaching its maximum allowed value (SOC_{max}). On the contrary, when SOC reaches its minimum allowed value ($\mathrm{SOC_{min}}$), charge controller disconnects the storage system in order to protect it. This methodology allows determine the amount of power that has been effectively stored in the battery.

The change in SOC from time $t-1$ to t can be used to determine the power required for reaching the level indicated by SOC_t incorporating charge controller operation; this idea is mathematically expressed in (6):

$$P_{C,t} = \frac{(SOC_t - SOC_{t-1})E_B^{max}}{\Delta t} \tag{6}$$

where $P_{C,t}$ is the power required to charge the battery until the level SOC_t; this value is related to the behavior presented in Fig. 2 through (7):

$$P_{C,t} = I_{S,t} V_{B,t} \tag{7}$$

Then, from the analysis of the circuit presented in (8)-(11), variables $V_{B,t}$ and $I_{B,t}$, and the corresponding power $P_{B,t}$ can be determined:

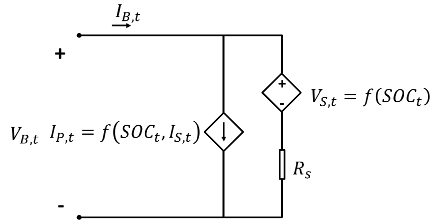

Figure 1. Electrical circuit model of VRB.

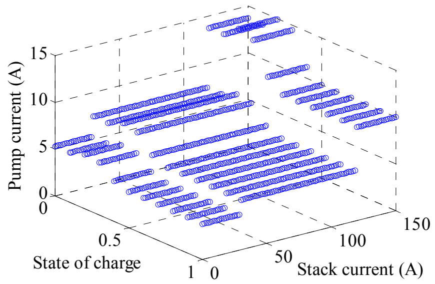

Figure 2. Power loss representation in VRB.

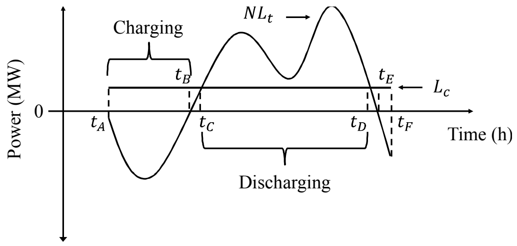

Figure 3. Charging and discharging strategy of VRB.

$$V_{B,t} = f(SOC_t) + \left(\frac{P_{C,t}}{V_{B,t}}\right) R_S \tag{8}$$

$$\left(V_{B,t}\right)^2 - \left(V_{B,t}\right) f(SOC_t) - P_{C,t}(R_S) = 0, \tag{9}$$

$$V_{B,t} = \frac{f(SOC_t) \pm \sqrt{[f(SOC_t)]^2 + 4P_{C,t}(R_S)}}{2}, \tag{10}$$

$$I_{B,t} = I_{S,t} + f\left(SOC_t, I_{S,t}\right), \tag{11}$$

As two possible voltage values can be obtained, that nearest to corresponding open circuit voltage is selected.

III. UNIT SCHEDULING DETERMINATION

Solving the unit commitment (UC) taking into account the mean characteristics of VRB is a difficult task due to the mathematical complexity of the elements involved. For this reason, in this work a methodology based on cycle charging strategy is proposed.

As stated before, the first step consists on determining charging and discharging periods over the scheduling horizon. This is carried out by analyzing the hourly net load profile (NL_t) obtained from the subtraction between the load forecasting (L_t) and wind power forecasting ($P_{W,t}^f$). As shown in Fig. 3, between t_A and t_B, and t_E and t_F, NL_t is negative, indicating that this is an excess of renewable generation which could be stored in VRB; L_C is the critic load value defined as the average of all those positive NL_t; in our example, the average of NL_t between t_B and t_E. Discharging periods are determined from those hours at which NL_t is higher than L_C; specifically between t_C and t_D. Finally, between t_B and t_C, t_D and t_E VRB is neither charged nor discharged. In other words, VRB is charged during those time periods with excess of renewable generation; then, this energy is stored and discharged only during the peak-load hours according to the value of critic load. In this way, excess of renewable power generation is effectively used for load leveling purposes. Once charging and discharging periods are identified, the second step consists on determining dynamic behavior of VRB. This is carried out by means of a simulation process according to sub-section II-B, obtaining the hourly values of $P_{B,t}$. Finally, UC problem including the impact of VRB on thermal and renewable generators is analyzed by solving MILP problem presented in (12)-(28) [11].

$$min \sum_{t=1}^{T} \sum_{i=1}^{I} z_t^i + x_t^i \tag{12}$$

$$z_t^i = \lambda_i u_t^i + \rho_i\left(P_{T,t}^i\right); \quad t = 1,2,\dots,T; \quad i = 1,2,\dots,I \tag{13}$$

$$\sum_{i=1}^{I} P_{T,t}^i + P_{W,t} = L_t + P_{B,t}; \quad t = 1,2,\dots,T \tag{14}$$

$$\sum_{i=1}^{I} MP_{T,t}^i \geq L_t + P_{B,t} + \Delta R_t + \Delta W_t; \quad t = 1,2,\dots,T \tag{15}$$

$$x_t^i = \varepsilon_i^l \left[u_t^i - \sum_{n=1}^{l} u_{t-n}^i\right]; \; l = 1,2,\dots,A_i; \quad t = 1,2,\dots,T; \quad i = 1,2,\dots,I \tag{16}$$

$$P_T^{i,min}\left(u_t^i\right) \leq P_{T,t}^i \leq MP_{T,t}^i; \quad t = 1,2,\dots,T \tag{17}$$

$$0 \leq MP_{T,t}^i \leq P_T^{i,max}\left(u_t^i\right); \quad t = 1,2,\dots,T \tag{18}$$

$$MP_{T,t}^i \leq P_{T,t-1}^i + \Delta RU_{T,i}\left(u_{t-1}^i\right) + \Delta SU_{T,i}\left[u_t^i - u_{t-1}^i\right] + P_T^{i,max}\left[1 - u_t^i\right]; \quad t = 1,2,\dots,T; \; i = 1,2,\dots,I \tag{19}$$

$$MP_{T,t}^i \leq P_T^{i,max}\left(u_{t+1}^i\right) + \Delta SD_{T,i}\left[u_t^i - u_{t+1}^i\right]; \quad t = 1,2,\dots,T-1; \quad i = 1,2,\dots,I \tag{20}$$

$$P_{T,t-1}^i - P_{T,t}^i \leq \Delta RD_{T,i}\left(u_t^i\right) + \Delta SD_{T,i}\left[u_{t-1}^i - u_t^i\right] + P_T^{i,max}\left[1 - u_{t-1}^i\right]; \; t = 1,2,\dots,T; \; i = 1,2,\dots,I \tag{21}$$

$$\sum_{t=1}^{k_i}\left[1 - u_t^i\right] = 0; i = 1,2,\dots,I \tag{22}$$

$$\sum_{q=t}^{t+MUT_i-1} u_q^i = MUT_i\left[u_t^i - u_{t-1}^i\right]; \quad t = k_i + 1,\dots,T - MUT_i + 1; \; i = 1,2,\dots,I \tag{23}$$

$$\sum_{q=t}^{T}\{u_q^i - [u_t^i - u_{t-1}^i]\} \geq 0;$$

$$t = T - MUT_i + 2, \dots, T;\; i = 1,2,\dots,I \quad (24)$$

$$\sum_{t=1}^{h_i} u_t^i = 0; i = 1,2,\dots,I \quad (25)$$

$$\sum_{q=t}^{t+MDT_i-1} [1 - u_q^i] \geq MDT_i[u_{t-1}^i - u_t^i];$$

$$t = h_i + 1, \dots, T - MDT_i + 1;\; i = 1,2,\dots,I \quad (26)$$

$$\sum_{q=t}^{T}\{1 - u_q^i - [u_{t-1}^i - u_t^i]\} \geq 0;$$

$$t = T - MDT_i + 2, \dots, T;\; i = 1,2,\dots,I \quad (27)$$

$$0 \leq P_{W,t} \leq P_{W,t}^f \quad (28)$$

In this formulation, z_t^i is fuel consumption cost of unit i; u_t^i represents the state of the unit i (1 if the unit is online and 0 in other case); λ_i and ρ_i are parameters of fuel consumption cost of unit i; $P_{T,t}^i$ is the power of thermal unit i; $P_{W,t}$ is the dispatched wind power.

Moreover, $MP_{T,t}^i$ is the maximum output power of unit i; ΔR_t is the portion of spinning reserve related to generators reliability; ΔW_t is the portion of reserve related to wind power forecasting error, x_t^i is the startup cost of unit i. The ε_i^l is the cost of interval l of startup cost discretization; $P_T^{i,min}$ and $P_T^{i,max}$ are the minimum and maximum output power of unit i, respectively; $\Delta RU_{T,i}$, $\Delta SU_{T,i}$, and $\Delta RD_{T,i}$ are the ramp-up, startup ramp rate and the ramp-down rate of unit i, respectively. Finally, k_i is the time that unit i must be online to fulfill minimum up time constraint, MUT_i is minimum up time of unit i, MDT_i is minimum down time; h_i is time that unit i must be offline to fulfill minimum down time constraint.

IV. CASE STUDY

The methodology previously described for optimal management of VRB integrated to insular systems is illustrated by means of the analysis of two case studies with 10 and 4 generators respectively, with different profiles of load and wind power generation. Several storage capacities are evaluated and the impact on the reduction of fuel consumption and generating cost are discussed. VRB model presented in sub-section II-B was implemented in MATLAB language, while solution of UC problem described in section III was implemented in GAMS language.

A. *Case Study A*

The first case study consists on the analysis of a power system of 10 units whose data was taken from [12]. For this case, forecasted load and wind generation are shown in Fig. 4. Hourly profile of net load is shown in Fig. 5, where charging and discharging periods can be easily recognized according to the procedure explained in section III.

As stated before, pump current of auxiliary systems was estimated by scaling the experimental information presented in [10]. Moreover, SOC was limited to SOC_{min}= 0.2 and SOC_{max}= 0.9, and the parameters γ = 1.1364 and δ = 0.2452 were obtained from data presented in [13]. Regarding spinning reserve requirements, the portions of reserve were assumed as $\Delta R_t = 0.1(L_t + P_{B,t})$ and $\Delta W_t = 0.05(P_{W,t}^f)$. Charge controller operation was represented by assuming α = 20 and β = 0.5.

Considering a VRB with rated energy of 1500 MWh and rated power of 500 MW, the scheduling process was carried out, obtaining the results shown in Fig. 6. Fig. 7 shows the power to be supplied by the conventional and renewable generators; as can be observed, as higher storage capacity is incorporated to the system, the higher is the wind power that can be accommodated to the system, and higher is the reduction on the peak-load. It is possible observing how VRB reaches its maximum SOC by storing the majority of excess of renewable generation produced during the hours of low load. Once this energy has been stored, it is used to reduce peak-load that occurs at around t=20h by discharging 150 MW between t=17h and t=24h; under these conditions cost saving estimated is 10.65%, approximately.

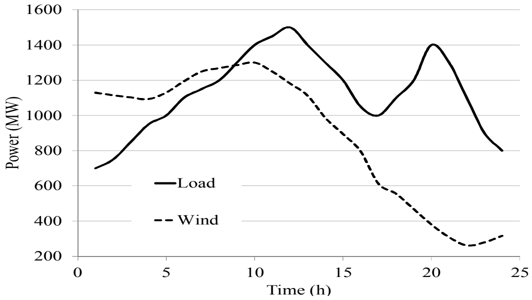

Figure 4. Wind power and load forecasting (Case A).

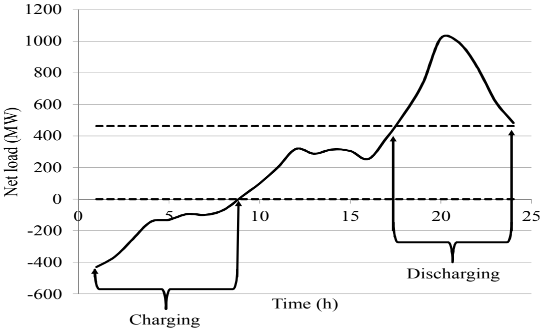

Figure 5. Net load, charging and discharging periods.

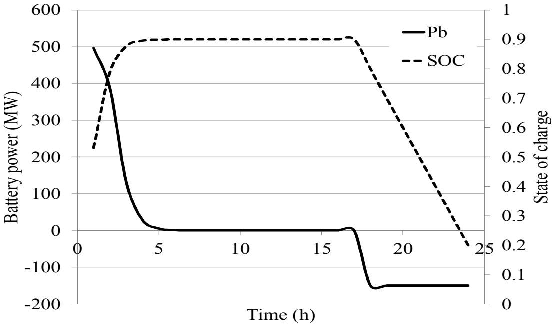

Figure 6. State of charge and power of VRB.

Fig. 8 shows the reduction on generating cost as the storage capacity is increased, according to these results the cost saving is between 3.36% and 25.3%.

B. Case Study B

The second case study consists on the analysis of a power system of 4 units whose data is presented in Table I; this data corresponds to diesel generators and was obtained by using information typically provided by manufacturers. Forecasted load and wind generation considered in this case study are shown in Fig. 9.

Fig. 10 presents the power to be supplied by thermal and wind generators. Fig. 11 presents the power to be supplied only by thermal generators.

Fig. 12 presents dispatched wind generation. Reader can note how integration of wind generation is increased as the storage capacity of the system is incremented in order to supply part of the energy required during high-load periods.

Fig. 13 presents the power to be supplied by thermal and wind generators. Similarly to our previous case study, VRB allows us accommodating the curtailed wind generation at low load periods (observed between t = 1h and t = 7h; as well as, between t = 22h and t = 24h, approximately) to be posteriorly used to reduce daily peak-loads (observed between t = 8h and t = 14h; as well as, t = 19h and t = 21h, approximately).

Fig. 14 shows the reduction of fuel consumption as storage capacity is increased, according to these results the reduction is between 1.35% and 10.85%.

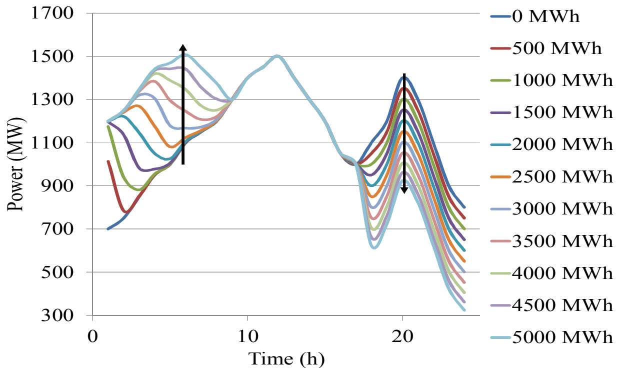

Figure 7. Power supplied by renewable and thermal units (Case A).

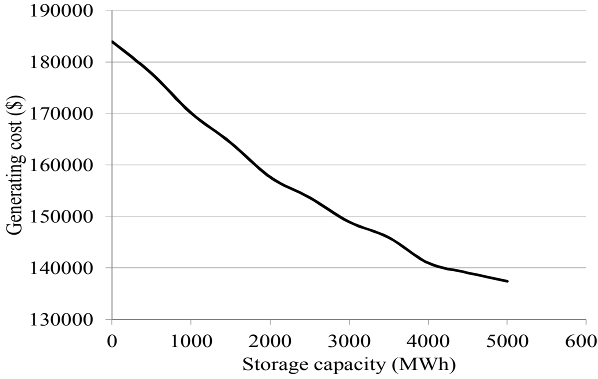

Figure 8. Generating cost for several storage capacities (Case A).

TABLE I. DATA OF CONVENTIONAL GENERATORS

i	$P_T^{i,max}$	λ_i (Gal/h)	ρ_i (Gal/kWh)
1	2000	7.95	0.0657
2	1500	6.1	0.0657
3	1250	5.15	0.0657
4	1000	4.25	0.0657

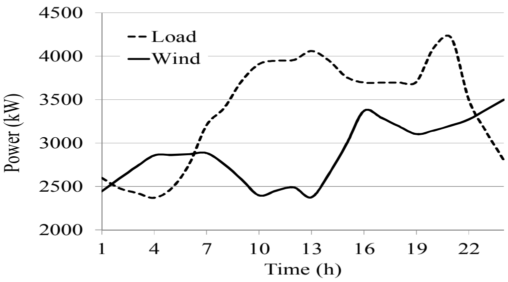

Figure 9. Wind power and load forecasting (Case B).

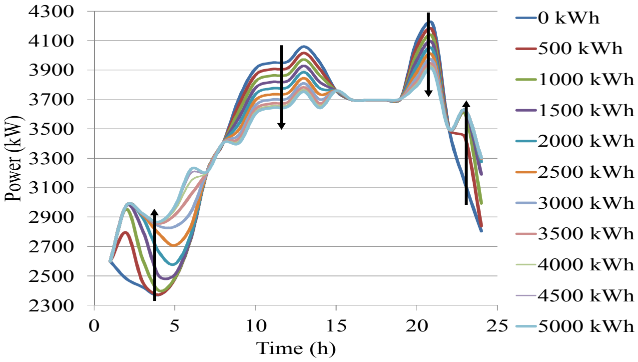

Figure 10. Power supplied by renewable and thermal units (Case B)

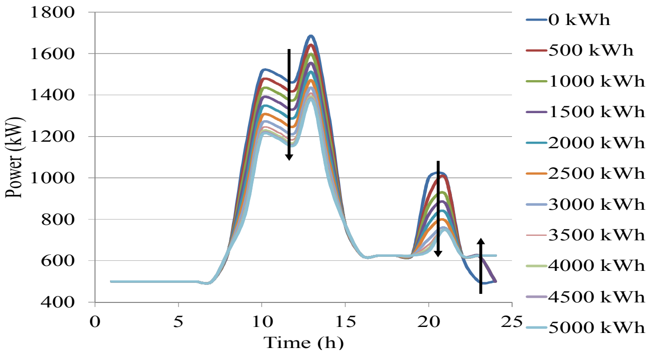

Figure 11. Power supplied by thermal units (Case B).

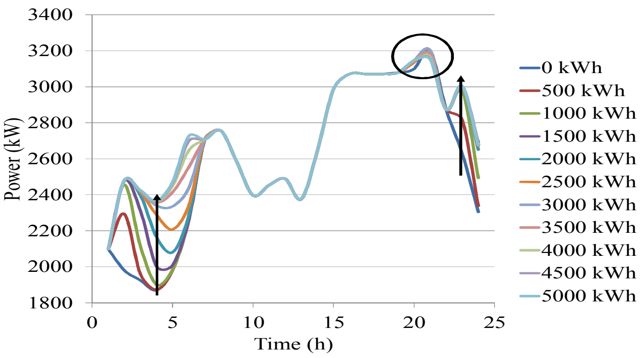

Figure 12. Dispatched wind generation (Case B).

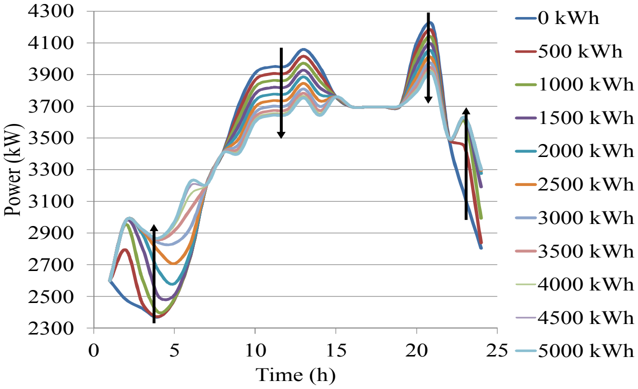

Figure 13. Power supplied by renewable and thermal units (Case B)

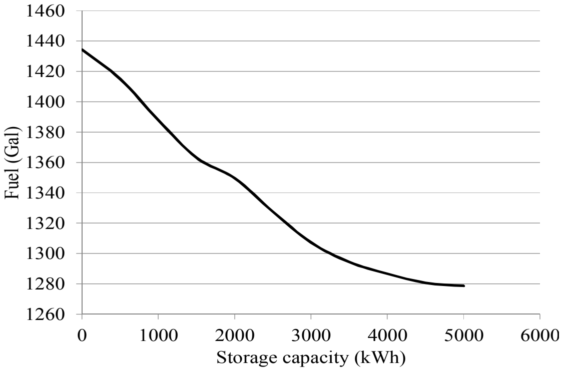

Figure 14. Fuel consumption for several storage capacities (Case B).

V. CONCLUSIONS

Integration of ESSs can increase power system flexibility enhancing renewable power accommodation. However, depending of the storage technology adopted, its optimal management could be a difficult task because of the non-linear characteristics and dynamic behavior. This work presented a methodology for optimal scheduling of isolated power systems provided of VRB, considering power requirements related to the auxiliary systems as well as charge controller operation. The proposed methodology consists of three main steps: First - charging and discharging period determination; Second - VRB dynamic behavior analysis; and Third - commitment and dispatch of thermal and renewable generation. From the analysis of two case studies, it was possible to verify the effectiveness of the proposed approach by improving the accommodation of wind generation, storing the excess of renewable generation at low load hours in order to be used later to reduce load demand at those hours of high load. This procedure allows improving generating efficiency of thermal units by enhancing the shape of energy demand profile to be supplied only by conventional generators. Results obtained from a sensibility analysis on the capacity of the storage system revealed that the reduction on generating cost and fuel consumption was between 1.35% and 25.3%, depending on the power system characteristics, renewable power generation profile, and penetration level.

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