

Evaluation of Reactive Power Capability by Optimal Control of Wind-Vanadium Redox Battery Stations in Electricity Market

A. Gabash¹ and P. Li¹

¹ Department of Simulation and Optimal Processes
Institute of Automation and Systems Engineering, Ilmenau University of Technology
98684 Ilmenau, Germany

Phone/Fax number: +0049 3677 69-2813/1434, e-mail: aouss.gabash@tu-ilmenau.de, pu.li@tu-ilmenau.de

Abstract. Battery energy storage systems (BESSs) integrated with renewable energy resources are considered as necessary solutions for economical, technical and quality aspects. A BESS requires a power conditioning system (PCS) which permits both active and reactive power to be generated. In this paper, a wind-vanadium redox battery (W-VRB) station is considered as an independent power producer. The profit of this producer is maximized by solving a constrained dynamic optimization problem in a day-ahead electricity market depending on real-time electricity prices. Then, the reactive power compensation capability of this station for fulfilling the recent technical guidelines is estimated. A numerical case study is presented to illustrate the proposed method. It can be concluded that a large amount of reactive power can be achieved by an optimal operating strategy for the W-VRB station.

Key words

Electricity market, optimization, wind-vanadium redox battery station, reactive power capability.

1. Introduction

Wind farms connected to distribution power systems are considered as “non-firm energy” (i.e. when they provide energy the generators in these wind farms are paid based on the output) and thus cannot be dispatched. Therefore, many studies have recently been carried out to make the wind farms at least hourly dispatchable. This can be achieved by integrating appropriate BESSs with these wind farms. However, in practice large-scale wind farms tend to maximize their profits in a day-ahead electricity market system. This can be made by optimizing the daily scheduling of their plants integrated with an appropriate energy storage system (ESS) such as pumped storage [1], [2], which can introduce both power and energy capabilities for dispatching power from wind farms. Another solution is to use a vanadium redox battery (VRB) [3] which will be developed for large capacity so that it could be used to substitute conventional pumped power storage stations [4].

In addition, a BESS to be connected to an AC power system requires a PCS [5] which provides a bidirectional power conversion between AC and DC systems. A PCS connected to the terminals of a BESS, as shown in Fig. 1,

permits it to generate both active and reactive power in all four quadrants, as shown in Fig. 2. Reactive power is needed for operating a wind farm. This can be either absorbed from the network where the wind farm is connected to, or generated locally. However, the recent technical guidelines [6] obligate the wind farms’ owners to provide both active and reactive power. Furthermore, the reactive power compensation capability of wind farms must fulfil the recent grid code requirements.

The most important issues related to the reactive power compensation capability of wind farms presented recently in the literature can be classified as follows [6]-[12]:

- Optimal reactive power flow
- Allocation of reactive power loss
- Optimal reactive power provision of wind farms
- Reactive power control and voltage regulation
- Reactive power support requirements during faults
- Low voltage ride through (LVRT) requirements

From the discussions above it is obvious that wind farms can be in the near future at least hourly dispatched for trading active power and fully controlled for reactive power.

In this paper, we consider the operation of W-VRB stations which are composed of two main substations, see Fig. 1. First, a wind farm substation which can hourly be dispatched. Second, a VRB substation in which its power and capacity are selected initially through simulation procedures and at the same time electricity market requirements can be satisfied. In addition, to maximize the profit of the W-VRB station for a day-ahead market system, a dynamic optimization problem depending on both a forecasted wind power profile and real-time electricity prices is formulated and solved where all operational constraints are satisfied. In this way, the reactive power compensation capability of this W-VRB station can be estimated. Solutions of this problem yield two active and reactive power bidding scenarios which are formulated hourly for one day-ahead. A case study is presented to evaluate the reactive power capability of the W-VRB station.

2. A W-VRB Station

Using BESSs with wind energy for power management assumptions for modelling a W-VRB station shown in Fig. 1 are made as follows:

- The wind farm substation, as seen in Fig. 1, can be dispatched on an hourly basis [13],[14], (i.e. hourly constant wind active power output $P_w(k)$ from the wind farm substation), where k denotes a time interval in hour.
- Typically, the power factor (PF) of a wind farm is controllable from 0.95 inductive to 0.95 capacitive [9]. We assume for simplicity a constant power factor for the wind farm substation with 0.962 inductive, which means absorbing reactive power, $Q_w(k)$.
- The VRB substation proposed in this study has two main parts: tanks and a PCS. The tanks are used to store the energy $E(k)$ in the form of chemical energy. The PCS is a flexible AC transmission system (FACTS) [15] controller based on a voltage source converter (VSC) rated and controlled to operate in all four quadrants: discharge, charge, leading VAR, or lagging VAR.
- During charge/discharge processes there are power losses. For simplicity we assume constant values of their efficiency to be during the charge (80%) and during the discharge (75%) [2].

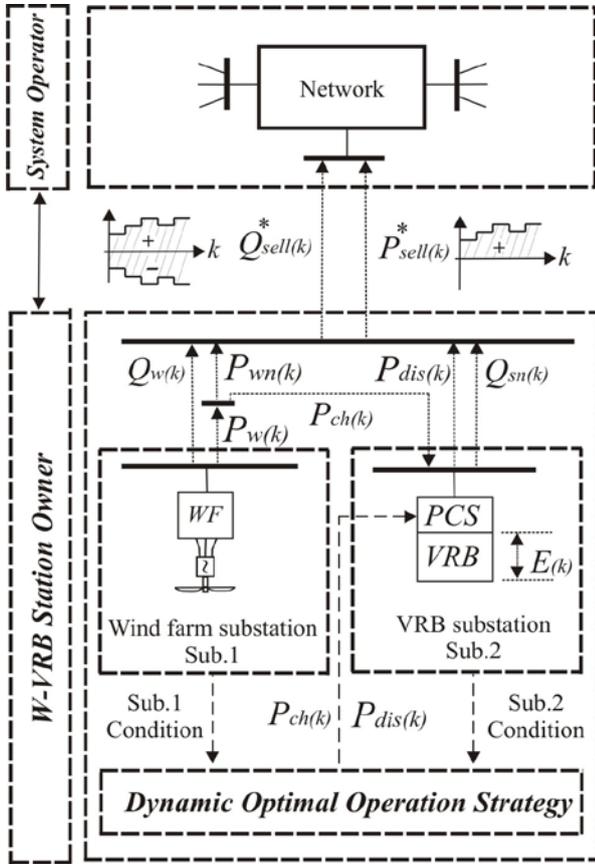


Fig.1. Structure of the proposed W-VRB station and the total scheme

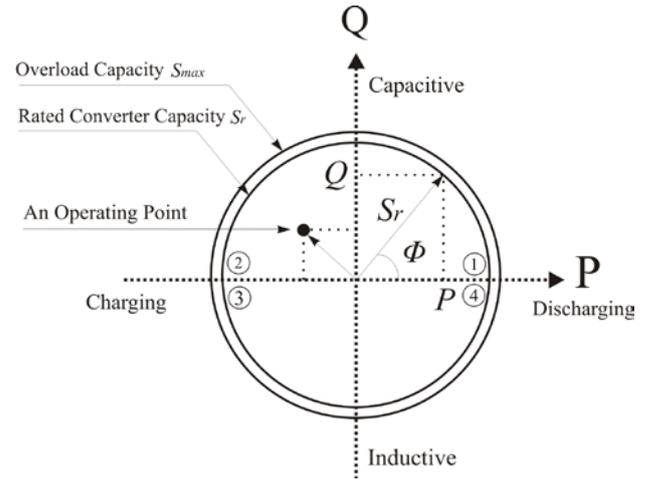


Fig.2. Active and reactive power capability of the PCS

3. Profit Maximization

Based on the above assumptions we formulate a dynamic optimization problem to maximize the profit of operating a W-VRB station for one day-ahead while all the operational constraints are satisfied.

A. Objective function

The objective function to be maximized is defined as Eq. (1) where the first summation term denotes the total revenue through active power trading in which the losses in the revenue by charging/discharging are subtracted. The second summation term is formulated to minimize the differences of control decisions between two time intervals in order to keep a smooth operation for evaluating the minimum constant reactive power capability. The weighting factor β balances the two terms leading to a balance of the profit and the amount of reactive power. In Eq. (1), $C_{pr}(k)$ represents a vector of hourly active power prices, $C_{ch}(k)$ the charge operation cost, $C_{dis}(k)$ the discharge operation cost, $P_{sell}(k)$ the hourly active power to be sold to the electrical power system, $P_{ch}(k)$ the hourly active power charged to the VRB substation and $P_{dis}(k)$ the hourly active power discharged to the network from the VRB substation, respectively.

$$\max \sum_{k=1}^{24} \left(C_{pr}(k)P_{sell}(k) - C_{ch}(k)P_{ch}(k) - C_{dis}(k)P_{dis}(k) - \beta \left((P_{ch}(k+1) - P_{ch}(k))^2 + (P_{dis}(k+1) - P_{dis}(k))^2 \right) \right) \quad (1)$$

B. Model equations

The equations (2-4) describe the active power exchanges in the model as well as the change in the energy level in substation 2. Equations (5-6) represent the initial and final energy levels.

$$P_{sell}(k) = P_{wn}(k) + P_{dis}(k) \quad (k = 1, \dots, 24) \quad (2)$$

$$P_w(k) = P_{wn}(k) + P_{ch}(k) \quad (k = 1, \dots, 24) \quad (3)$$

$$E(k) = E(k-1) + \eta_{ch} P_{ch}(k) \Delta t - (1/\eta_{dis}) P_{dis}(k) \Delta t \quad (k=1, \dots, 24) \quad (4)$$

$$E(0) = E_{start} \quad (5)$$

$$E(24) = E_{end} \quad (6)$$

The time interval Δt is considered to be one hour. In these model equations $P_{wn}(k)$ denotes the hourly active power delivered to the network by the wind farm, $P_w(k)$ the hourly available wind power for a given wind speed scenario, $E(k)$ the energy storage level in the VRB substation in each hour, respectively. E_{start} and E_{end} are the assumed initial and final energy storage levels, respectively, for the considered time horizon. It should be noted that these values can increase or decrease the profit of the W-VRB station, see Fig. 5. However, practically they can be selected to be the same value to take the next time horizon into account. In Eq. (4) η_{ch} , η_{dis} are the charge and discharge efficiency of the VRB substation, respectively.

C. Operation Constraints

The operation constraints (7-11) are introduced for satisfying the technical requirements of the whole system and ensuring all variables to be in their upper and lower bounds as shown below:

$$P_{sell.min}(k) \leq P_{sell}(k) \leq P_{sell.max}(k) \quad (k=1, \dots, 24) \quad (7)$$

$$0 \leq P_{wn}(k) \leq P_w(k) \quad (k=1, \dots, 24) \quad (8)$$

$$0 \leq P_{ch}(k) \leq S_r(k) \quad (k=1, \dots, 24) \quad (9)$$

$$0 \leq P_{dis}(k) \leq S_r(k) \quad (k=1, \dots, 24) \quad (10)$$

$$E_{min} \leq E(k) \leq E_{max} \quad (k=1, \dots, 24) \quad (11)$$

where $P_{sell.min}(k)$ and $P_{sell.max}(k)$ are the hourly minimum and maximum active power output, respectively, required from the W-VRB station that satisfies both market and network requirements. S_{max} and S_r are the maximum (overload capacity for short time) and rated apparent power of the proposed and selected PCS to be suitable for the VRB substation, respectively. E_{max} and E_{min} are the maximum and minimum constraints on the energy storage levels, respectively. After solving this optimization problem $P_{ch}(k)$ and $P_{dis}(k)$ scenarios can be obtained. Then the hourly available reactive power from the VRB substation $Q_{sn}(k)$ can be calculated as follows [16]:

$$Q_{sn}(k) = \begin{cases} \sqrt{S_r^2 - P_{ch}^2(k)} & \text{if charging} \quad (k=1, \dots, 24) \\ \sqrt{S_r^2 - P_{dis}^2(k)} & \text{if discharging} \quad (k=1, \dots, 24) \end{cases} \quad (12)$$

In this way, the available reactive power to be sold to the electrical power system $Q_{sell}(k)^*$ can be calculated using Eq. (13)

$$Q_{sell}(k)^* = Q_{sn}(k) + Q_w(k) \quad (k=1, \dots, 24) \quad (13)$$

where $Q_w(k)$ is the hourly reactive power of the wind farm substation which is set to work with the fixed power factor

($\cos \Phi = 0.962$) lagging (i.e. absorbing reactive power) as described by Eq. (14).

$$Q_w(k) = P_w(k) \tan \Phi \quad (k=1, \dots, 24) \quad (14)$$

4. A Case Study

The optimization problem defined in section 3 is solved under the MATLAB environment, using FMINCON function [17] which can find a minimum/maximum (maximization is achieved by supplying optimization routines with $-f$, where f is the function being optimized) of a constrained nonlinear multivariable function. Practically, real-time spot prices are available as a scenario for one day-ahead, as shown in Fig. 3.

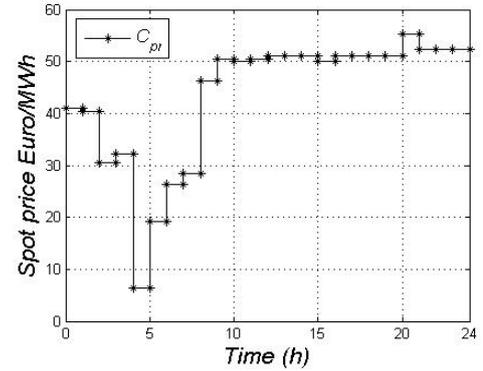


Fig.3. Real-time spot prices for one day-ahead (01.11.2010) (www.eex.com)

All values given in this work are in per unit (pu), unless otherwise specified. The base power is selected to be 100 MVA. We consider the price scenario and the wind active power output P_w as shown Fig. 4 and the data given in Table I.

Table I: Case study data

C_{ch}	C_{dis}	β	η_{ch}	η_{dis}	E_{start}
€MWh	€MWh	-	%	%	MWh
3.5	2.15	8	80	75	10
E_{end}	$P_{sell.min}$	$P_{sell.max}$	S_r	E_{min}	E_{max}
MWh	MW	MW	MVA	MWh	MWh
10	2	8	3	4.5	18

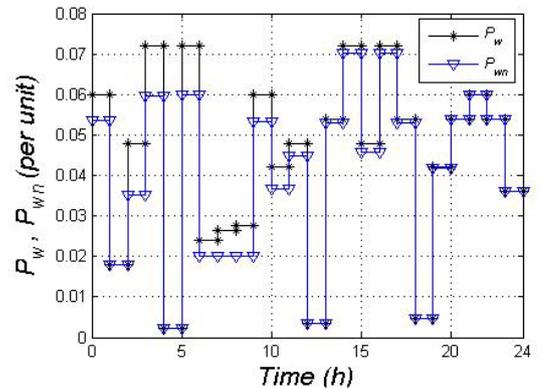


Fig.4. Wind active power output and the active power from the wind farm substation to the network

We solved the optimization problem by selecting initially the rated power of the PCS to be $S_r = 0.03$ pu. In Fig. 5 the optimal energy level and their changes is shown and in Fig. 6 the optimal sold active power scenario is illustrated. With this initial value the optimization yields the available constant reactive power from the W-VRB station shown in Fig. 7 (it could be sold to the electrical power system).

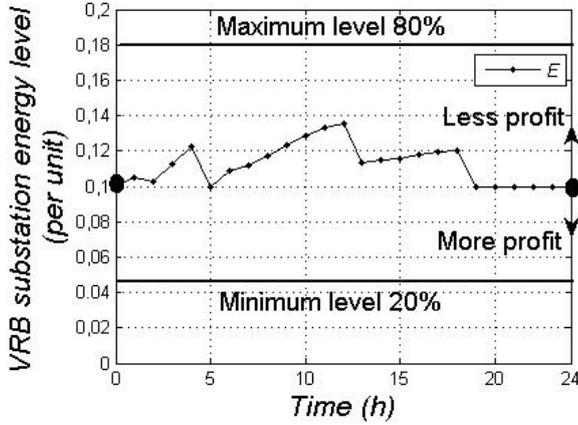


Fig.5. Optimal energy level of the VRB substation, when $S_r = S_l = 0.03$ pu, $\beta=8$ and $E_{end}=10$ MWh.

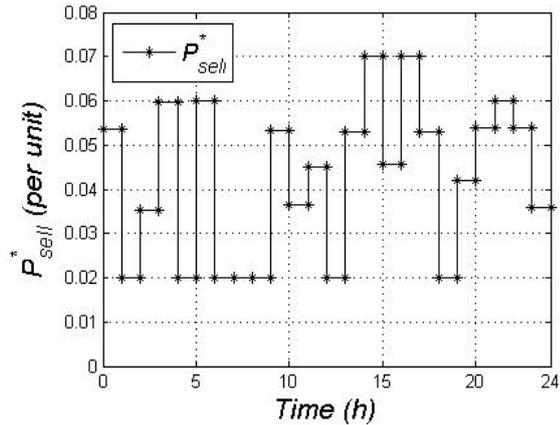


Fig.6. Optimal active power output offering from the W-VRB stations on the wholesale market when $S_r = S_l = 0.03$ pu, $\beta=8$ and $E_{end}=10$ MWh.

The results show that the available reactive power gained by solving the optimization problem depends on the selection of the weighting factor β . It can be increased by expanding the rated power dimension (d) of the PCS by a selected expanding ratio (n). In Fig. 8 the capability of the PCS is shown, where S_l is the initial assumed rated power of the PCS and S_5 is the extended rated power. Fig. 9 shows the available constant reactive power from the W-VRB station where $n = 5$. It should be noted that the expanding ratio n of the PCS to be decided depends actually on the demand of reactive power that must be available at a specific point of a given power network. The resulting constant reactive power scenario could be used by the system operator for satisfying multiple issues related to reactive power compensation capability as discussed above in Section 1.

We define the constant (inductive/capacitive) reactive power which is available from a W-VRB station to be sold

to the electrical power system in a day-ahead electricity market system as the W-VRB station reactive power capability ($Q_{W-VRB.Capability}$).

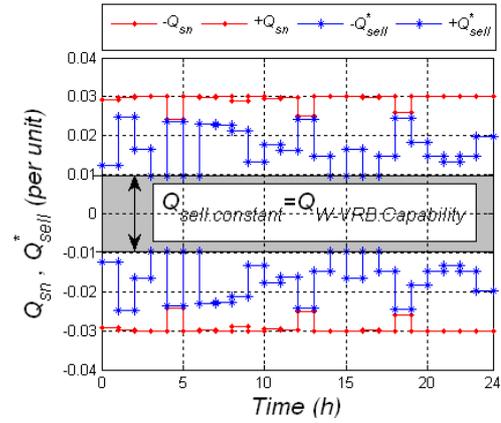


Fig.7. Available constant reactive power to be sold from the W-VRB station when $S_r = S_l = 0.03$ pu, $\beta=8$ and $E_{end}=10$ MWh.

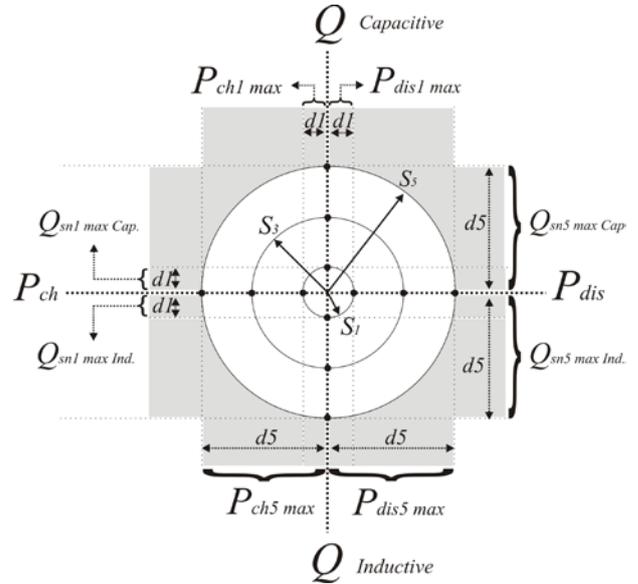


Fig.8. Extending active and reactive power capability of the PCS

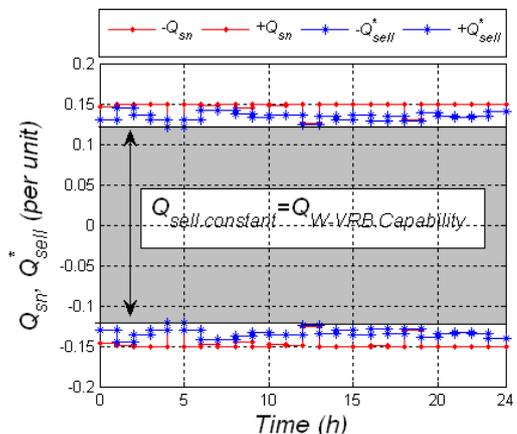


Fig.9. Available constant reactive power to be sold from the W-VRB station when $S_r = S_5 = 0.15$ pu, $\beta=8$ and $E_{end}=10$ MWh.

In (14), we define two functions (f_1, f_2) to study the effect of selection the weighting factor β . f_1 describes the relationship between the W-VRB station profit in one day-ahead and the weighting factor β at multi rated powers of the PCS. f_2 stands for the relationship between the reactive power capability (as defined above) and the weighting factor β . $S_1 = S_r(base) = 3$ MVA, $S_5 = n * S_r(base) = 15$ MVA ($base$ denotes the initial assumed rated power of the PCS), where $n = 5$ is the expanding ratio. Fig. 10 shows the computation diagram which is implemented under MATLAB. In Fig. 10 Last_n denotes the last rated power of the PCS to be evaluated, and Last_Beta denotes the last value of the weighting factor β to be selected. From the computation results it is shown that the range of $\beta = (0-20)$ is enough for the evaluation process, since the reactive power capability will not increase any more and the profit will still decrease linearly, if the weighting factor increases further, see Fig. 11 and Fig. 12.

The profit of the W-VRB station for one-day-ahead and its reactive power capability can be achieved as follows:

$$\left. \begin{cases} f_1(\beta) = Profit & = \max \sum_{k=1}^{24} C_{pr}(k) P_{sell}(k) \\ f_2(\beta) = Q_{W-VRB.Capability} & = \min (Q_{sell}^*(k)) \end{cases} \right\}_{S_r=constant} \quad (k=1, \dots, 24) \quad (14)$$

The profit of the W-VRB station is dependent on selecting the weighting factor as shown in Fig.11. However, using an increasing weighting factor β , this will lead to a smooth operation of the W-VRB station during power charging/discharging and to increasing the reactive power capability. Another point to be mentioned from the results is that by extending the active and reactive power capability of the PCS from $S_1 = 3$ MVA to $S_3 = 9$ MVA (see Fig. 8), there is a small increase in the W-VRB station profit, see Fig. 11.

It can clearly be noted from the profiles in Fig.12 that using a weighting factor β more than 10 will not noticeably increase the reactive power capability of the W-VRB station in a day-ahead electricity market.

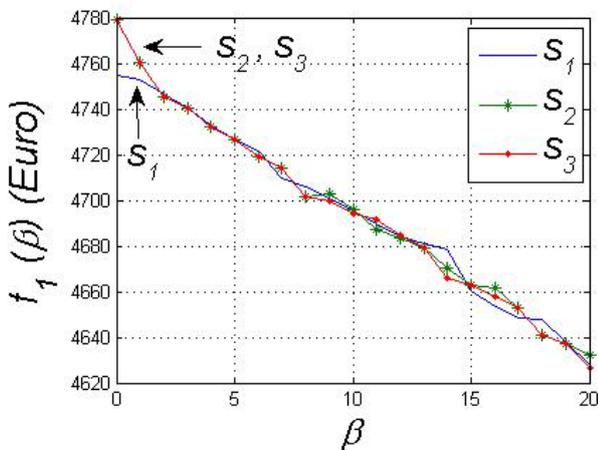


Fig.11. Relationship between the W-VRB station profit and the weighting factor β , where $E_{end} = 8$ MWh.

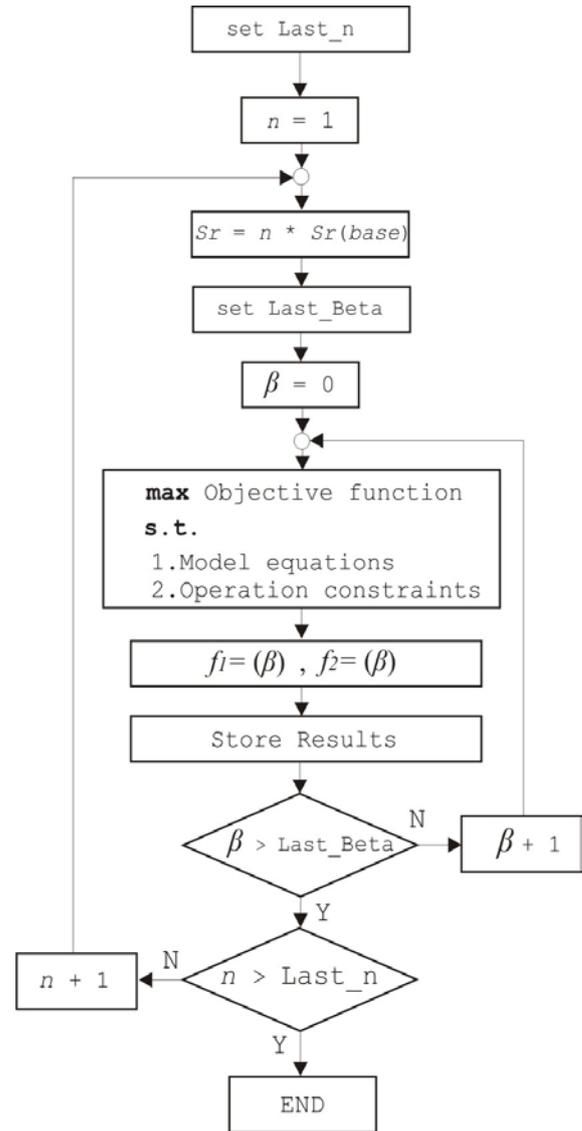


Fig.10. Computation diagram for the W-VRB station profit and the W-VRB station reactive power capability.

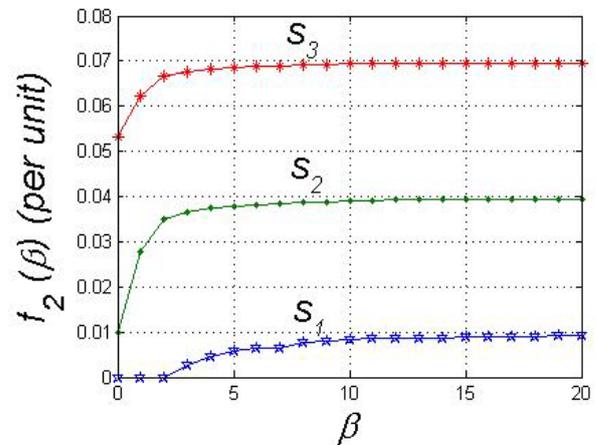


Fig.12. Relationship between the W-VRB station reactive power capability and the weighting factor β , where $E_{end} = 8$ MWh.

5. Conclusions

In this paper, a method was proposed for both maximizing the profit of a W-VRB station operation in a day-ahead electricity market and fulfilling the last technical guidelines regarding reactive power compensation capability of wind farms. This can be achieved by solving a constrained dynamic optimization problem in which the profit and the amount of available reactive power can be balanced. It can be shown that a W-VRB station can provide a large amount of reactive power which can be fully controlled by using a suitable power conditioning system. This reactive power can satisfy the local reactive power demand of the wind farms and provide sufficient, constant and fully controlled reactive power to the electrical power system.

In the future this reactive power capability from a W-VRB station can be utilized, either without the necessity of installing other reactive power compensators such as Static synchronous Compensator (STATCOM) and Mechanically-Switched Capacitors and Reactors (MSCR), or it can be used in a hybrid reactive power sources system by a dynamic optimal operation of the reactive power sources at the W-VRB station. In addition, this reactive power compensation can be supplied to the electrical power system as a fully controlled reactive power source with constant available amount of reactive power which can be used to exchange the reactive power with the electrical power system, as in the active power trading of the W-VRB station. Moreover, this reactive power capability could be sold to the electrical power system as a constant reactive power scenario for satisfying multiple tasks such as increasing power quality, voltage regulation, power losses minimization, low voltage ride through LVRT issues, increasing the individual revenue of wind farms through their reactive power compensation capabilities and so on.

Acknowledgement

The research was supported by the Ministry of Higher Education of the Syrian Arab Republic.

References

- [1] E.D. Castronuovo, and J.A.P. Lopes, "On the optimization of the daily operation of a wind-hydro power plant" in IEEE Transactions on Power Systems, Aug. 2004, Vol. 19, No. 3, pp. 1599-1606.
- [2] D.K. Khatod, V. Pant, and J. Sharma, "Optimized daily scheduling of wind-pumped hydro plants for a day-ahead electricity market system" in Third International Conference on Power Systems, Kharagpur, India, Dec. 2009, pp. 1-6.
- [3] J. Chahwan, C. Abbey, and G. Joos, "VRB Modelling for the Study of Output Terminal Voltages, Internal Losses and Performance" in IEEE Canada Electrical Power Conference EPC, Montreal, Que., Oct. 2007, pp. 387-392.
- [4] S. Miyake, and N. Tokuda, "Vanadium redox-flow battery for a variety of applications" in IEEE Power Engineering Society Summer Meeting, Vancouver, BC, Jul. 2001, pp. 450-451.
- [5] N.W. Miller, R.S. Zrebiec, G. Hunt, and R.W. Deimerico, "Design and commissioning of a 5 MVA, 2.5 MWh battery energy storage system" in IEEE Proceedings Transmission and Distribution Conference, Los Angeles, CA, Aug. 2007, pp. 339-345.
- [6] M. Tsili, and S. Papathanassiou, "A review of grid code technical requirements for wind farms" in IET Renewable Power Generation, Sep. 2009, Vol. 3, No. 3, pp. 308 - 332.
- [7] P.M.D. Oliveira, P.M. Jesus, E.D. Castronuovo, and M.T. Leao, "Optimal Reactive Power Provision of Wind Farms in Liberalized Markets - A Generation Viewpoint" in IEEE PES Transmission and Distribution Conference and Exhibition, Dallas, TX, May. 2006, pp. 295-300.
- [8] P.M.D. Oliveira, P.M. Jesus, E.D. Castronuovo, and M.T. Leao, "Reactive Power Response of Wind Generators Under an Incremental Network-Loss Allocation Approach" in IEEE Transactions on Energy Conversion, June. 2008, Vol. 23, No. 2, pp. 612-621.
- [9] E. Diaz-Dorado, C. Carrillo, and J. Cidras, "Control Algorithm for Coordinated Reactive Power Compensation in a Wind Park" in IEEE Transactions on Energy Conversion, Dec. 2008, Vol. 23, No. 4, pp. 1064-1072.
- [10] A.F. Zobaa, and M. Jovanovic, "A Comprehensive Overview on Reactive Power Compensation Technologies for Wind Power Applications" in International Power Electronics and Motion Control Conference, Portoroz, Aug. 2006, pp. 1848-1852.
- [11] E. Camm, and C. Edwards, "Reactive compensation systems for large wind farms" in IEEE/PES Transmission and Distribution Conference and Exposition, Chicago, IL, Apr. 2008, pp. 1-5.
- [12] E. Diaz-Dorado, C. Carrillo, and J. Cidras, "Control Algorithm for Coordinated Reactive Power Compensation in a Wind Park" in IEEE Transactions on Energy Conversion, Dec. 2008, Vol. 23, No. 4, pp. 1064-1072.
- [13] S. Teleke, M.E. Baran, A.Q. Huang, S. Bhattacharya, and L. Anderson, "Control Strategies for Battery Energy Storage for Wind Farm Dispatching" in IEEE Transactions on Energy Conversion, Sept. 2009, Vol. 24, No. 3, pp. 725-732.
- [14] S. Teleke, M.E. Baran, S. Bhattacharya, and A.Q. Huang, "Optimal Control of Battery Energy Storage for Wind Farm Dispatching" in IEEE Transactions on Energy Conversion, Sept. 2010, Vol. 25, No. 3, pp. 787-794.
- [15] K. R. Padiyar, "FACTS Controllers in power transmission and distribution", New Age International (P) Ltd., Publishers. New Delhi, 2007.
- [16] E. Muljadi, C.P. Butterfield, R. Yinger, and H. Romanowitz, "Energy Storage and Reactive Power Compensator in a Large Wind Farm" in AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 2004, pp. 1-10.
- [17] <http://www.mathworks.com>