PROVIDING ANCILLARY SERVICES IN DISTRIBUTION NETWORKS WITH VANADIUM REDOX FLOW BATTERIES: ALPSTORE PROJECT

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ABSTRACT

This paper deals with voltage regulation in low voltage networks with converter connected photovoltaic and storage units (Vanadium Redox Flow Batteries – VRB). It presents a decoupled current control method applied to the production of reactive power of the PV-VRB converter. The aim of this control strategy is to ensure appropriate voltage profile and increase the integration of renewable distributed generation units into the distribution networks.

INTRODUCTION

In the development of electric power system, countries must achieve ambitious targets to meet key environmental commitments. This will increase the reliability of energy supply, reduce the impact on the environment, and also provide economic growth and the development of jobs and employment.

Today it is generally accepted that Smart Grids are key element of the future power systems and an enabling factor to meet the above commitments. The concept of Smart Grids is an upgrade of the existing concept of operation and design of the power system. It involves the individual elements of the system, both classical and new elements, such as the distributed generation (DG) resources, advanced measurement systems, flexible prosumers, virtual power plants, electric cars and energy storage systems.

Electricity storage technologies are part of the Smart Grid concept. Since these technologies are at different stages of development, the primary aim of this paper will be to show possibilities of employing VRB storage technology that is available on the marker to provide ancillary services in distribution networks. Some of the functionalities that can be realized using VRB technology are:

- Island operation (IO) capabilities,
- Peak power shaving functionality;
- Estimation of savings in the construction (development) of the electricity network (reinforcements), if storage units are added to the large consumers;
- Transfer of nocturnal energy in use during the day;
- The balancing of schedules;
- Voltage support.

In this paper, voltage support functionalities of the VRB technology together with the PV system will be demonstrated by means of numerical simulations.

PILOT PROJECT

Within the AlpStore research project framework, an experimental prototype has been implemented in the Slovenian remote Alpine Space area. Main goal of the pilot project is to show benefits of employing storage technologies in such areas, where small villages are often supplied by a long (radial) overhead distribution lines. As these lines are heavily exposed to the external influences (trees, snow ...) that are causing short-circuits on the line, short- and long-term power supply interruption are more often than average. Also, connecting DG unit at the end of such lines, can cause unacceptable voltage deviations. First results obtained by numerical simulations show promising capabilities of the proposed control strategies for the future design of such systems. Simplified scheme of the pilot project (simulation case) is shown in Tab. 1 and Fig. 1.

Tab. 1: Basic technical characteristics of the pilot project.

Module	Power	Other
VRB	10 kW	48 V_{dc}
PV	10 kW	70 m^2
Electronics	10 kW	48-56 V_{dc}

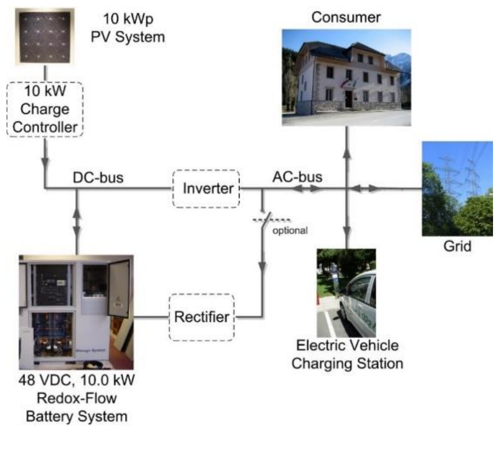
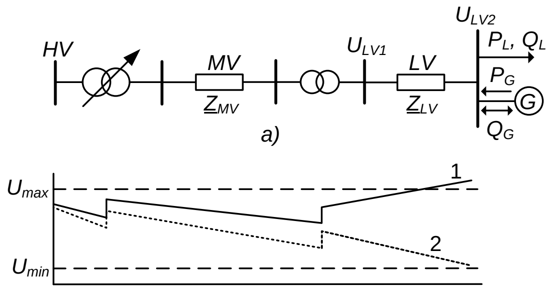


Fig. 1: Simplified scheme of the pilot project: flow battery, PV generation unit and electric car charging station.

VOLTAGE PROFILE IN LOW VOLTAGE DISTRIBUTION NETWORKS

Impact of DG units on voltage profile

Fig. 2 shows an example of a distribution feeder and its voltage profile. Nowadays voltage regulation in



1) Low load, DG connected
2) High load, DG disconnected

b)

Fig.2. a) Simple model of a distribution network, b) voltage profile.

distribution networks is carried out mainly by automatic tap changers at the HV/MV transformers. The MV/LV transformers are usually without automatic tap changers, however, depending on the voltage conditions in the network, transformer's tap changer can be adjusted manually under the off-load conditions. The tap changer should be set so that the voltage along the entire length of the distribution line is within the prescribed limits (+6/–10% for the low voltage in Slovenia) [5, 6].

Fig. 2–b shows voltage profile along the feeder for an example without DG (dotted line). As it can be seen, the voltage is raised at both transformers to ensure the appropriate voltage level. Thus, it can happen that the voltage at the end of the feeder exceeds the maximum allowed value (full line). In principle, this can be prevented by lowering the voltage of the HV/MV transformer and thus bring the voltage at the end of the feeder below the upper limit. However, one should be aware that there are usually several feeders connected to the HV/MV and MV/LV transformers. If there are no DG units connected to these feeders, it is very likely that their voltage will be unacceptably low if the voltage at the HV/MV transformer is lowered [7].

Voltage regulation facilities

In networks with distributed generation the following methods of maintaining proper voltage levels are possible:

- reinforcement of the network,
- DG reactive power control,
- DG active power control,
- installation of voltage regulators,
- use of compensators.

Apart from the reinforcement of the network all other methods represent an active approach of voltage regulation. For the last two methods from the list installation of some additional equipment is required, while regulating the voltage with active and reactive power control usually does not require any additional equipment.

Distributed generation power control

The voltage drop value along the LV line is given by (see Fig. 2):

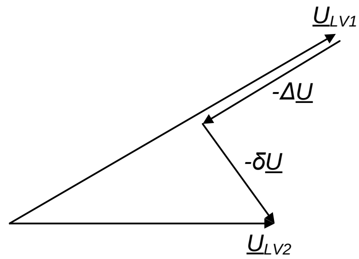


Fig. 3. Voltage drop phasor diagram.

$$\underline{U}_{LV2} = \underline{U}_{LV1} - \frac{R_L P + X_L Q}{\underline{U}_{LV2}} - j\frac{X_L P + R_L Q}{\underline{U}_{LV2}}, \qquad (1)$$

where $\underline{U}_{LV2} = U_{LV2}\angle 0°$ is set as a reference voltage and P and Q are, consecutively, the real and imaginary parts of the apparent power at DG point of common coupling (PCC).

Fig. 3 shows the voltage phasor diagram described by (1). From the Fig. 3 it can be concluded that the difference in voltage amplitudes $\underline{U}_{LV1}$ and $\underline{U}_{LV2}$ is mainly due to the component $\Delta\underline{U}$, which is in phase with the phasor $\underline{U}_{LV1}$. The difference in phase angle between $\underline{U}_{LV1}$ and $\underline{U}_{LV2}$ is mainly due to the imaginary component $\delta\underline{U}$. Voltage amplitude at the generator PCC can therefore be approximated as:

$$U_{LV2} \approx U_{LV1} - \frac{RP_L}{U_{LV2}} + \frac{RP_G}{U_{LV2}} - \frac{XQ_L}{U_{LV2}} \pm \frac{XQ_G}{U_{LV2}}, \qquad (2)$$

where the relations $P = P_L - P_G$ and $Q = Q_L \pm Q_G$ were considered. Assuming the extreme case ($P_L = 0$ and $Q_L = 0$), the voltage at DG connection point can be expressed as:

$$U_{LV2} \approx U_{LV1} + \frac{RP_G}{U_{LV2}} \pm \frac{XQ_G}{U_{LV2}}. \qquad (3)$$

From (3) it can be seen, that the voltage U_{LV2} at the DG PCC may be higher than the voltage U_{LV1} at the MV-side of the transformer and is in direct relationship with the power produced by the DG. Therefore, controlling the DG power production offers a very straightforward method of voltage control. This can be done either by reducing the generated active power P_G or by absorbing the reactive power Q_G.

Maintaining an adequate voltage profile by regulating the reactive power is more common in the transmission system, where power lines are longer and the R/X ratio is lower, which means that the impact of reactive power on voltage is higher. Despite the fact that the distribution network's R/X ratio is larger (typically around 1) and the impact on voltage by reactive power is lower, the reactive power control can still contribute to maintaining voltage within the limits set by the standards [8-9].

VOLTAGE REGULATION BY DISTRIBUTED GENERATION REACTIVE POWER CONTROL

In this section a decoupled current control method applied to the production of reactive power of a PV-VRB system is presented. Beside the basic function, i.e. delivering the active power to the grid, the algorithm also enables the reactive power control.

Derivation of the voltage control algorithm

The voltage control algorithm is based on the VSC d-q mathematical model [4]. At first, the *d*- and *q*-axis current components have to be decoupled. This is done by removing all the adjustable parameters and elements containing ω and introducing three new variables (v'_{pd}, v'_{pq} and v'_{dc}). The modified VSC mathematical model is given by equations 4, 5 and 6. The model is simplified to three first order functions.

$$\frac{d}{dt}\begin{bmatrix} i'_{pd} \\ i'_{pq} \\ u'_{DC} \end{bmatrix} = \begin{bmatrix} \frac{-R'_p \omega_B}{L'_p} & 0 & 0 \\ 0 & \frac{-R'_p \omega_B}{L'_p} & 0 \\ 0 & 0 & \frac{-\omega_B C'}{R'_C} \end{bmatrix} \cdot \begin{bmatrix} i'_{pd} \\ i'_{pq} \\ u'_{DC} \end{bmatrix} + \begin{bmatrix} v'_{pd} \\ v'_{pq} \\ v'_{dc} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} v'_{pd} \\ v'_{pq} \\ v'_{DC} \end{bmatrix} = [A_1] \begin{bmatrix} i'_{pd} \\ i'_{pq} \\ u'_{DC} \end{bmatrix} + \begin{bmatrix} \frac{\omega_B}{L'_p} u'_{id} \\ \frac{\omega_B}{L'_p} u'_{iq} \\ -C' \omega_B i'_{DC,sol} \end{bmatrix} \tag{5}$$

$$[A_1] = \begin{bmatrix} 0 & 0 & \frac{-k_p \omega_B}{L'_p} S_d \\ 0 & 0 & \frac{-k_p \omega_B}{L'_p} S_q \\ \frac{3k_p \omega_B C'}{2} S_d & \frac{3k_p \omega_B C'}{2} S_q & 0 \end{bmatrix} \tag{6}$$

Figures 4 and 5 show the principle of reactive power control. A linear droop characteristic is used to calculate the reactive power set point Q_{ref}, using voltage deviation at the PCC of DG as the control input. Droop control is widely used in multiple generator systems as a load-sharing scheme. The droop characteristic describes how a

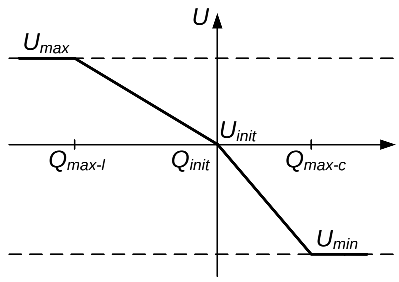


Fig.4. Voltage control droop characteristic.

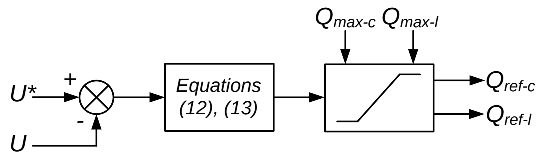


Fig.5. Reactive power control block diagram.

reactive compensating unit responds to voltage changes. Each slope characteristic is determined by a nominal voltage set point U_{init} and two droops (7) and (8).

$$s_c = \frac{U_{init} - U_{\min}}{Q_{\max-c} - Q_{init}} \tag{7}$$

$$s_l = \frac{U_{\max} - U_{init}}{Q_{init} - Q_{\max-l}} \tag{8}$$

Quantities used in (7) and (8) are as follows: Q_{init} – initial reactive power injection/consumption, U_{init} – initial (nominal) voltage and Q_{max-l}, Q_{max-c} – inductive and capacitive reactive power boundary values.

For example, a 0.1 reactive power slope means that a 10 % voltage deviation causes 100% change in reactive power output. In general, the slopes (7) and (8) may be different (as shown in Fig. 4) and are determined with the permitted voltage deviation and with reactive power boundary values [10].

The DG reactive power reference values are calculated according to the equations (9) and (10):

$$Q_{ref-c} = Q_{\max-c} \frac{U_{init} - U}{s_c \cdot U_{init}}, \tag{9}$$

$$Q_{ref-l} = Q_{\max-l} \frac{U_{init} - U}{s_l \cdot U_{init}}. \tag{10}$$

Maximum reactive power values Q_{max-c} and Q_{max-l} can be determined in a fixed manner or depending on the production of the active power [11]. In this paper, reactive power boundary values are fixed according to the rated apparent power of the converter.

Fig. 6 shows a simplified control algorithm scheme. The inputs to the algorithm are formed by the difference between the reference and actual values of currents ($\Delta i'_{pd}$

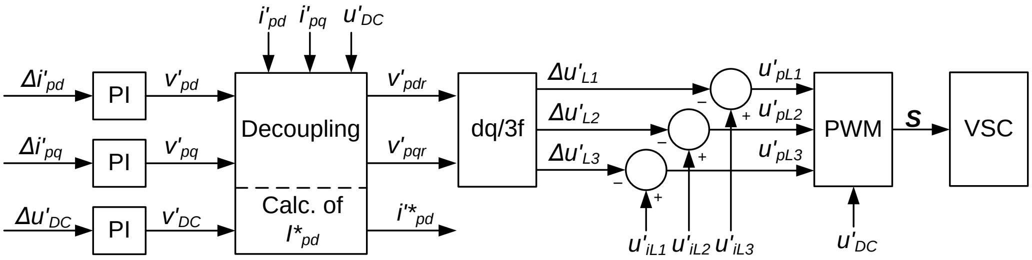


Fig. 6. Simplified control system scheme.

and $\Delta i'_{pq}$) and the difference between the reference and actual value of dc voltage ($\Delta u'_{dc}$). The reference value of the current i'_{pq} is defined by Q_{ref} – see Fig. 5. From PI controllers the necessary voltage drops on the coupling inductance and the required dc current to maintain a constant DC voltage are obtained. In the next step v'_{pd} and v'_{pq} are decoupled and converted to the three-phase system. The reference current $i'_{pd}*$ is also calculated. After subtracting the actual voltages of all three phases (u'_{iL1}, u'_{iL2} and u'_{iL3}), we obtain the required voltages to be generated at the PV-VRB VSC output (u'_{pL1}, u'_{pL2} and u'_{pL3}).

SIMULATION RESULTS

To illustrate some practical implications of the proposed reactive power output control and voltage regulation in distribution networks a simulation case is presented. Simulations were carried out in the PSCAD software.

The simulated distribution network with integrated PV and VRB system is shown in Fig. 7. The network consists of a power transformer TR 1 (S_{TR1} = 630 kVA, u_{SC} = 4 %), a PV-VRB system and two radial distribution lines (r = 0.86 Ω/km, x = 0.81 Ω/km, l_1 = 100 m, l_2 = 200 m), modelled with impedances Z_1 and Z_2. The power consumption at the end of each line is illustrated by the impedances Z_{L1} and Z_{L2} (R_{L1} = 1.44 Ω, L_{L1} = 0.0015 H, R_{L2} = 2.88 Ω, L_{L2} = 0.0031 H). The remaining distribution network was simulated as a stiff voltage source with a short-circuit impedance connected in series (S_{SC}'' = 190 MVA). Droop characteristic data were as follows: the initial reactive power set point Q_{init} = 0 p.u. (U_{init} = 1 p.u.), the capacitive droop s_C = 0.1 and the inductive droop s_L = 0.06.

Simulation results are shown in Tab. 2. The results are given as per-unit values of voltages at bus 1 and bus 2 for four different cases: without DG (case 1), no voltage regulation (case 2), reactive power voltage regulation (case 3) and voltage regulation by limiting the production of active power (case 4). Due to the low voltage at bus 2, the voltage at the supply transformer is raised to 1.04 p.u. From the table it can be seen that the voltage at bus 1 exceeds the maximum allowed value of 1.06 p.u. in the case without voltage regulation (case 2). In case 3, the voltage is lowered using presented reactive power voltage control.

Reactive power consumption of 0.38 p.u. effectively reduces the voltage to 1.03 p.u. – well below the maximum

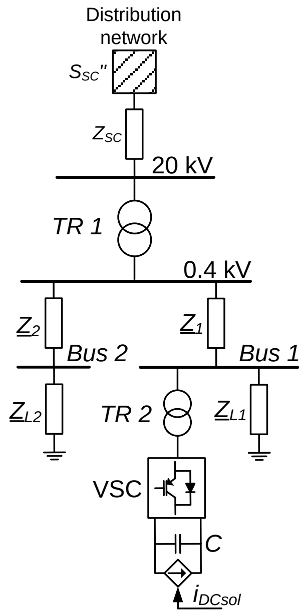


Fig.7. A simplified scheme of the modelled distribution network with shunt-connected VSC with PV-VRB generation system.

Tab. 2: Simulation results – voltages at buses 1 and 2, and power injection for four cases in per-unit.

	Case 1	Case 2	Case 3	Case 4
Bus 1 voltage	1.00	1.07	1.03	1.03
Bus 2 voltage	0.91	0.91	0.90	0.91
P	0	0.70	0.70	0.22
Q	0	0	-0.38	0

Note: 0.4 kV, 50 Hz, 150 kVA, base.

limit. The same result can also be achieved by active power curtailment. The active power generation has to be limited to 0.22 p.u. (i.e. 31 % of the rated power).

CONCLUSION

In this paper a decoupled current control strategy for DG reactive power voltage control was presented. Simulation results showed that PV-VRB DG with the proposed reactive power control is capable of effectively compensating the voltage rise, while maintaining constant active power injection (see Tab. 1).

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