Electric Power Systems Research 134 (2016) 167–175

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Potential of using DC voltage restoration reserve for HVDC grids

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form 5 January 2016
Accepted 9 January 2016
Available online 11 February 2016

Keywords:
HVDC grids
Reserves
Power systems
Ancillary services

ABSTRACT

Any electric power system has to maintain an energy equilibrium at every moment. This is the case for existing AC systems and will be the case for future HVDC grids. Otherwise, the frequency will fluctuate beyond acceptable values, as will the voltage in DC grids. Therefore, energy balancing services are needed to manage both quantities. This paper defines reserve steps for HVDC grids, in analogy to the reserves for AC systems as implemented in Europe. It shows that if the HVDC grid reaches a certain scale, the services can be organised in a similar way as existing AC reserves. In this paper, the focus lies on the DC secondary reserve/DC voltage restoration reserve. The introduction of such reserves will benefit the system through increased stability, damping of small or slow unpredicted fluctuations and the option to organise a DC system in multiple control areas.

1. Introduction

The ongoing paradigm shift in generation philosophy requires an adaptation of the connecting transmission system. The increase of renewable energy generation makes high voltage direct current (HVDC) increasingly viable over traditional AC. The advantages of HVDC technology are longer transmission distances, a smaller footprint for the same bulk power transmission, and the simpler implementation of offshore and underground systems, due to absence of reactive power [1,2]. This results in an increasing number of projects for point-to-point HVDC connections around the world [3–5]. As the use of HVDC increases, it becomes more reliable and economical to connect point-to-point connections and form a meshed grid [6]. Such a DC grid has to be operated in a similar manner as existing AC grids [7]. One important commonality is that both grids have to hold an energy balance. Although, in DC grids, the DC voltage represents the balance of infeeds and withdrawals plus losses, it cannot be assumed to be a global parameter throughout the system as is the frequency in AC grids, since the current causes a voltage drop over the line resistances. However, there are advantages to keeping the DC voltage in a defined range, for example: loss minimisation [8] and decrease of interactions between AC and DC grids. Within the last years, several solutions were proposed to maintain the energy balance in an HVDC grid [9–12]. These solutions can be compared to primary control actions in AC systems and they have similar limitations, namely a permanent change of DC node voltages due to a change of power set points of the involved converter stations, which is not necessarily predictable [13]. If DC grids arise and reach a certain size and power rating, this drawback can no longer be accepted if reliability were to be the same as in existing AC grids [14,15]. This problem is also identified in [16] and a solution is presented. However, it does not take into account that a DC grid could consist of several control areas. Thus, this work presents a general controller for DC grids that achieves different control areas as well. It describes the control structure and implements it in the simulation software DIgSILENT PowerFactory to show the functionality. Since the controller actions are related to reserves, the paper also presents a definition of DC reserves in analogy to the European AC reserves as they are described in the ENTSO-E network code [17].

2. Definition of DC grid reserve steps

A multiple steps reserve is implemented in most AC systems to maintain the energy balance. In continental Europe, it is implemented in the form of frequency containment reserve (FCR), or primary reserve, frequency restoration reserve (FRR), or secondary reserve and replacement reserve (RR), or tertiary reserve [17]. After

Abbreviations: ACE, area control error; DCRR, DC replacement reserve; DCVCR, DC voltage containment reserve; DCVRR, DC voltage restoration reserve; ENTSO-E, European Network of Transmission System Operators for Electricity; FCR, frequency containment reserve; FRR, frequency restoration reserve; HVDC, high voltage direct current; IGBT, insulated-gate bipolar transistor; MMC, modular multi-level converters; RR, replacement reserve; VSC, voltage source converters.

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http://dx.doi.org/10.1016/j.epsr.2016.01.006
0378-7796/

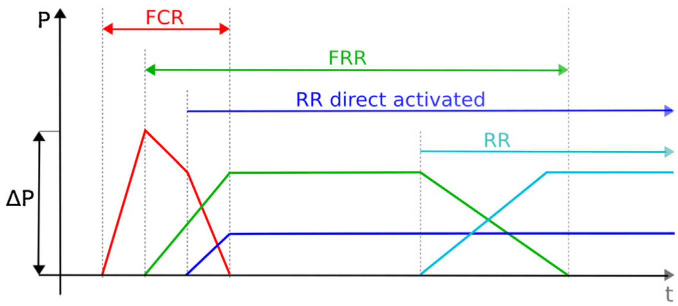

Fig. 1. Hierarchy of reserve steps in case of a power imbalance.

a considerable disturbance, the activation sequence of the three reserve steps is as shown in Fig. 1.

FCR is immediately activated after an outage of appreciable generation or load. It is realised as a proportional controller that is arranged in a decentralised manner. Thus, a P-controller is installed in each power plant that participates in FCR. The response happens without communication to other power plants, but is based on a local frequency measurement. Furthermore, it does not react in a band of maximum 20 mHz [17] in continental Europe.

FRR is tasked with bringing the system back to a defined state after such a disturbance, including restoration of scheduled power exchanges between control areas. In addition, it compensates for small and slow changes in the energy balance during normal operation. FRR control is centralised at the control area level. It requires communication to get information on actual and scheduled power exchanges of a certain area as well as the energy balance of the whole system. Utilising this data, the FRR will restore the energy balance of its control area and re-establish the power exchanges to agreed levels by changing the set points of individual units. This control action is, in Europe, performed in intervals of maximum 30 s [17].

RR is slower than FRR, typically activated manually and no longer relevant for this paper.

The combination of reserve steps increases the reliability of the system and reduces unwanted exchanges between control areas [2,14]. Thus, this paper introduces, in analogy to the reserve steps in AC power systems, the following names for DC grids:

- DC voltage containment reserve (DCVCR), or DC primary reserve,
- DC voltage restoration reserve (DCVRR), or DC secondary reserve,
- DC replacement reserve (DCRR), or DC tertiary reserve.

Each of these DC reserves must behave in an equivalent manner to their AC counterparts. Therefore, the DCVCR should react as fast as possible, which means without communication and using a proportional controller with the drawback of a permanent control deviation. The much slower DCVRR is tasked with compensating for the DCVCR if a major loss of infeed or withdrawal has disturbed the DC grid energy balance and, during normal operation, to compensate for small or slow variations and maintain the scheduled power exchange between control areas.

The remainder of this paper is organised as follows: Section 3 analyses the stored energy in DC grid capacitances and if DCVCR can operate with a DC voltage deadband. It is followed by Section 4 that describes controller settings and designs for DCVCR and DCVRR. Then, Section 5 discusses the influence of converter configuration and Section 6 validates the models used. Section 7 defines a case study and compares the theory with simulation results of stored energy in DC grids and Section 8 shows simulation results for DCVRR after a major outage and during small or slow power fluctuations. Finally, Section 9 gives a conclusion and describes further work.

3. Stored energy in converter stations and AC power plants

To estimate the stored buffer energy in future HVDC grids, an analysis of existing technology is performed. Both the used converter technology and the voltage level have an influence on the converter capacitance. Existing two- and three-level converters have a time constant between 5 and 10 ms, while the increasingly popular modular multi-level converters (MMC) have a time constant of up to 60 ms [18,19]. With the current limit determined by the IGBT [3,4], the only variable to increase the power is the voltage. Although the arrangement of the capacitors in MMCs differs from two-level converters, a representation of the converters as two-level converters with an adjusted time constant is sufficient for this paper [20].

Therefore, Eq. (1) represents the relationship between capacitance C, charge or discharge duration t with constant power P, and a voltage change from $u(0)$ to $u(t)$ [21].

$$\Delta E_{\mathrm{Cap}} = P \cdot t = \frac{1}{2} \cdot u(t)^2 \cdot C - \frac{1}{2} \cdot u(0)^2 \cdot C \tag{1}$$

Furthermore, capacitances in voltage source converters (VSC) depend on the rated power P_{r}, the nominal voltage U_{N} and the time constant τ. Thus, Eq. (1) can be rewritten in terms of the time constant τ (with $u(\tau) = u(0) \cdot e^{-1}$, $U_{\mathrm{N}} = u(0)$ and $-P_{\mathrm{r}} = P$):

$$\tau = \frac{C \cdot \left((U_{\mathrm{N}} \cdot e^{-1})^2 - U_{\mathrm{N}}^2 \right)}{2 \cdot (-P_{\mathrm{r}})} \tag{2}$$

This can be written as

$$\Rightarrow C = \frac{2 \cdot I_{\mathrm{r}} \cdot \tau}{U_{\mathrm{N}} \cdot (1 - e^{-2})} \tag{3}$$

The result of Eq. (3) is for converter ratings of 1.667 kA and ±300 kV between approximately 0.032 mF for a time constant of 5 ms to around 0.39 mF for a time constant of 60 ms. Combining (1) and (3) results in:

$$\Delta E_{\mathrm{Cap}} = \left(\frac{P_{\mathrm{r}} \cdot \tau}{U_{\mathrm{N}}^2 \cdot (1 - e^{-2})} \right) \cdot (u(t)^2 - u(0)^2) \tag{4}$$

A similar relationship exist for mechanical power:

$$\Rightarrow \Delta E_{\mathrm{Rot}} = P_{\mathrm{Rot}} \cdot t = \frac{1}{2} \cdot J(\omega(t)^2 - \omega(0)^2) \tag{5}$$

where E_{Rot} = stored energy in the rotating mass, J = the moment of inertia, $\omega(t)$ = angular frequency at the time t, and $\omega(0)$ = angular frequency at the time 0. There is a wide variation of power plans and their moment of inertia J, respectively inertia constant H. Thereby, H sets the rated apparent power S_{r} of a power plant in relationship to the stored energy in the rotating mass E_{Rot} when it is rotating at nominal speed, i.e.

$$H = \frac{E_{\mathrm{Rot}}}{S_{\mathrm{r}}} \tag{6}$$

Eq. (5) can be written dependent of (6) [15].

$$\Delta E_{\mathrm{Rot}} = \frac{H \cdot S_{\mathrm{r}}}{\omega_{\mathrm{N}}^2} \cdot (\omega(t)^2 - \omega(0)^2) \tag{7}$$

H is typically from $2\,\frac{\mathrm{MWs}}{\mathrm{MVA}}$ (Hydropower plant) to $10\,\frac{\mathrm{MWs}}{\mathrm{MVA}}$ (large steam turbine) [15]. This results in stored energy ranging from 2000 to 10,000 MWs for a power plant with a rated apparent power of 1000 MVA and a nominal frequency of 50 Hz. This is much more than the 11.6 MWs (0.032 mF) to 69.4 MWs (0.39 mF) stored in the capacitors of a converter with 1000 MW rated power and 600 kV nominal DC voltage. However, for the secondary response, it is not the total stored energy that is interesting, but rather the distribution over the excepted frequency, respectively DC voltage range. Fig. 2 shows the available energy for a change from the nominal