Impact of Voltage Sags on DC Bus Voltage in Unipolar LVDC Systems

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1. Introduction – The number of dc loads and devices, such as computers, lightning systems, TVs or adjustable speed drives (ASDs), in homes and offices has increased dramatically in the past few years. For this reason, research on dc grids has become increasingly prominent not only on high-voltage dc (HVDC) transmissions between offshore wind parks and onshore grids [1] but also on low-voltage dc grids for developing rural areas, residential buildings, commercial facilities, universities or data centers [2]-[5]. The main advantages of dc grids are: i) higher system efficiency because of lower inverter conversion losses between dc output sources and loads, and ii) no need to consider synchronization with the utility grid or reactive power.

Although future low-voltage dc grids will include a large number of distributed generations, some current projects are made as passive grids, as in ac systems [6]-[8] (Fig. 1). These grids have no bidirectional power flux and are implemented with uncontrolled rectifiers.

Dc systems with passive front end are very sensitive to voltage sags [9]. Voltage sags, the most frequent grid disturbance, are responsible for most industrial process interruptions [10][11]. These interruptions are mainly due to the disconnection of the converter, i.e., converter protection tripping. Despite the disruption of operation, voltage sags do not usually result in equipment damage [12].

The main protections of VSI-fed ASDs used in industry are against, dc bus undervoltage during sags and large inrush currents during or at the end of the sag for I^2t rating of diodes.

This paper presents a study on the impact of voltage sags on dc bus voltage in unipolar LVDC systems based on an ABB converter. Dc bus response to a voltage sag in the ac grid is measured and simulated to analyze the influence of voltage sag characteristics (residual voltage or depth h and duration Δt) and the system's equivalent capacity on the minimum dc bus ($u_{d,min}$) voltage.

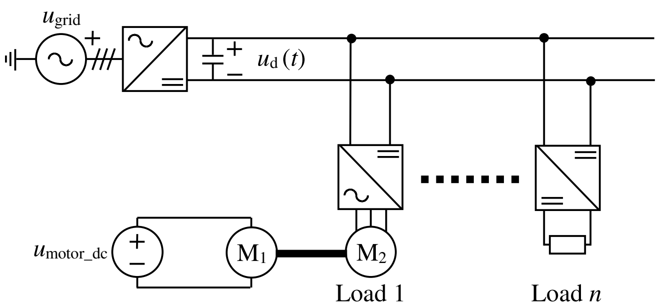

Figure 1. Structure of the LVDC grid

2. Voltage Sag Characterization and Classification - Voltage sags are short-duration reductions in the rms voltage mainly due to short-circuit faults. A voltage sag is characterized by four parameters [13], namely duration (Δt), depth (h), fault current angle (ψ) and sag type. Three-phase faults generate symmetrical sags, i.e., type A sags, while one- and two-phase faults generate unsymmetrical sags, i.e., type B, C, D, E, F and G sags. This classification is given in [11].

Faults are cleared at fault-current zeros; that is, fault-clearing does not occur instantaneously but in different steps, resulting in a *discrete* voltage recovery. The ways to fully clear the same type of fault are classified into fourteen groups in [13], five of which refer to symmetrical sags (named A_1, A_2, A_3, A_4 and A_5) while the other nine refer to unsymmetrical sags (denoted as B, C, D, E_1, E_2, F_1, F_2, G_1 and G_2). According to [14], sag type B is a particular case of sag type D, and sag types E and G are equivalent as they have identical positive- and negative-sequence voltages.

3. Experimental Setup and Simulations- Dc voltage response to symmetrical and unsymmetrical voltage sags was studied with laboratory measurements on a low-voltage dc grid and PSCAD simulations.

The laboratory setup included a three-phase diode rectifier based on an ABB ASD (ACS 143-4K1-3), an adjustable speed drive (ASD), an induction motor, a programmable three-phase voltage source, a dc adjustable speed drive mechanically coupled to the induction motor (which fixed the shaft speed and operated as a load), resistances, speed and current sensors and a torque transducer mounted on the shaft (Fig. 2).

Voltage sag patterns with discrete voltage recovery were generated by Simulink and applied to the voltage source through a DSPACE card.

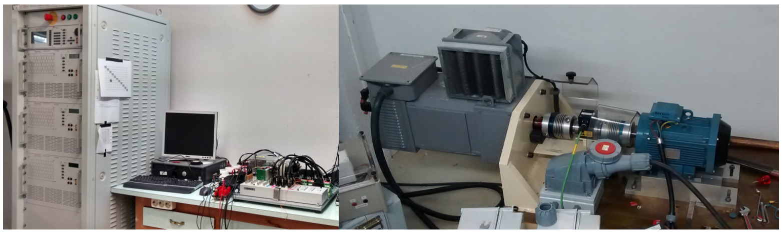

Figure 2. Experimental setup

In all cases, the ac line voltage was set to $U = 400$ V and the frequency was $f = 50$ Hz.

4. Voltage Sag Effects - Fig. 3 plots the measured dc voltage against symmetrical and unsymmetrical voltage sags with the following characteristics: $h = 0.7$, $\Delta t = 5T$, $\psi = 80º$. The magnitude is given in relatives values, where $U_b = 1.35 \cdot U_N$.

As can be seen, a voltage sag is a temporary reduction of the grid voltages. Its main effects on the dc voltage are dc undervoltage, dc overvoltage at grid voltage recovery and dc ripple. These effects can cause the tripping of LVDC system protections.

As in the system in Fig. 1, there is no distributed generation that can support the dc bus in the presence of a voltage sag. Then, the system can collapse if a minimum threshold, i.e., the minimum voltage required for stability of the system, is reached.

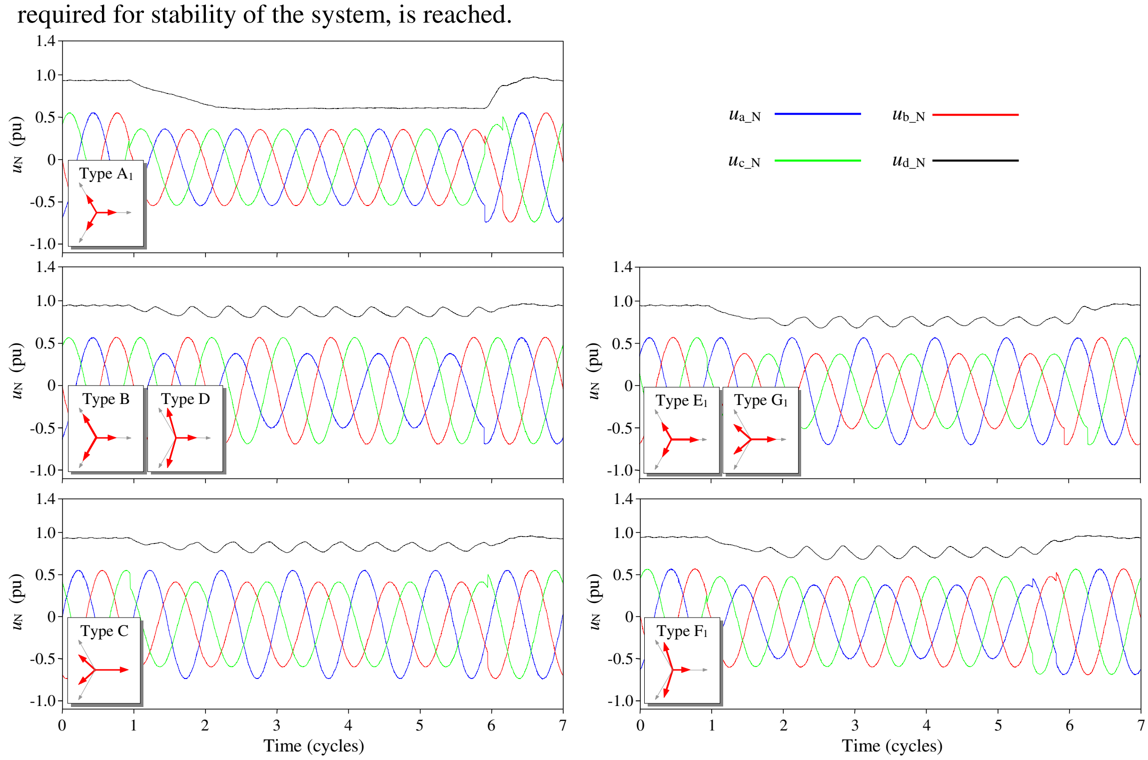

Figure 3. Measured effects of type A_I, B, C, D, E_I, F_I, G_I sags of characteristics $\Delta t = 5T$, $\psi = 80º$, $h = 0.7$.

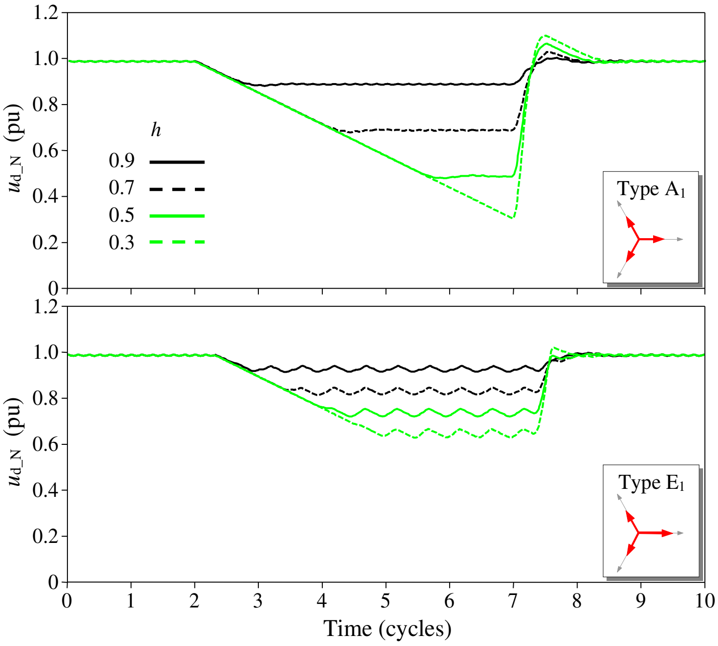

Figure 4. Analysis of dc voltage for different voltage sag depths.

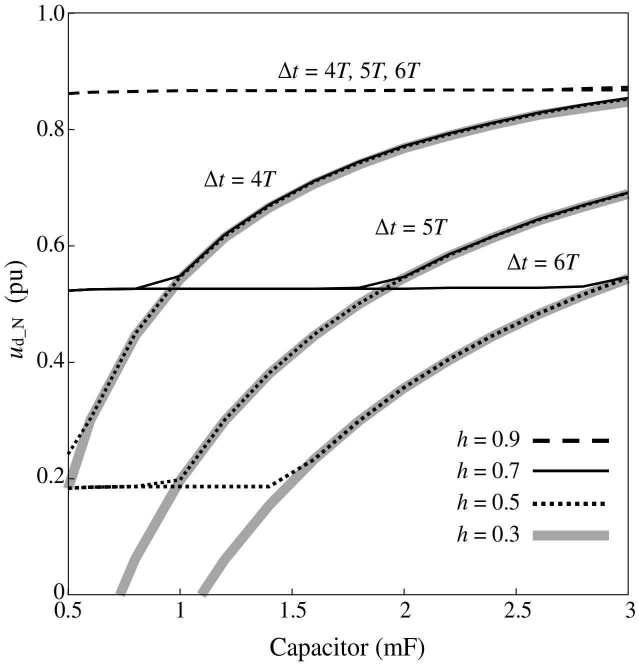

Figure 5. Analysis of dc voltage for different symmetrical voltage sag characteristics.

Symmetrical voltage sags are the most severe cases (A_1 in Fig. 3) because the dc voltage is reduced according to sag depth. On the other hand, the main effect of unsymmetrical voltages sags is the presence of a ripple in the dc voltage. However, the reduction of the dc voltage mean value is less severe for two-phase (type E_1) and single-phase (type B) voltage sags. For type C and F_1 sags, the consequences are similar to those reported for the previous cases.

Standard IEC60364 [15] on low-voltage electrical installations (up to 1500 V) requires that dc voltage ripple must be in the 10% range of rated dc voltage. This threshold is sometimes violated in the event of voltage sag. Moreover, overvoltage due to ac voltage recovery can result in protection tripping or equipment damage. This overvoltage depends on the discharge state of the equivalent capacitor. Thus, the more discharged a capacitor is, the higher the voltage peak.

Fig. 4 plots the depth (h) impact on the simulated system. As can be seen, more severe voltage sags result in lower voltage values. Overvoltage at grid voltage recovery is also shown.

Finally, Fig. 5 shows the minimum voltage obtained under different conditions as a function of dc capacitor size, and voltage sag depth (h) and duration ($\Delta t = 4T$, $5T$ and $6T$). The strong influence of capacitor size is worth noting. Thus, larger capacitors result in higher low voltage values. This can be related to sag duration since large capacitors take longer to discharge. This can be a simple immunity method for very short sags. For less severe voltage sags ($h = 0.9$), the minimum dc voltage practically does not depend on capacitor size.

Another consequence of the capacitance increase is the large currents during charging stages, which can lead to system protection tripping.

4. Conclusions - This work dealt with the behavior of the dc bus voltage in a low-voltage dc grid under a symmetrical or unsymmetrical voltage sag in the ac grid. Time measurements and simulations of this behavior were provided. The main effects of voltage sags are lower mean values of the dc voltage and the presence of ripple in the event of unsymmetrical voltage sags. Voltage sag characteristics and dc capacitor influence on the minimum dc voltage were also analyzed. It can be concluded that low-voltage dc grids must include dc undervoltage and overvoltage protections.

5. References

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