ON DIMENSIONING LVDC NETWORK CAPACITANCES AND IMPACT ON POWER LOSSES

Andrey LANA
LUT – Finland
andrey.lana@lut.fi

Tero KAIPIA
Pasi NUUTINEN
Tuomo LINDH

Jarmo PARTANEN
LUT - Finland
jarmo.partanen@lut.fi

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY (LUT) - Finland
name.surname@lut.fi

ABSTRACT

The DC network capacitance sizes affect on both the technical performance and the economy of the low voltage direct current (LVDC) distribution network. For instance, the power losses of the LVDC network depend from the dimensioning of the capacitors. This paper focuses on presenting the principles of DC capacitance dimensioning in LVDC power distribution network with directional power flow. Analytical calculation approach is used to define DC capacitance sizes. Effect on power losses in network is provided. Results are tested by means of simulation in PSCAD/EMTDC environment with a simulation model verified against measurements on laboratory prototype system.

INTRODUCTION

Reliable electricity distribution and high-power quality have become vital for the efficient functioning of modern society. At the same time there are pressures to increase the cost efficiency and the energy efficiency of the distribution networks. Power electronics is increasingly applied to various everyday technologies and it is breaking through also in electricity distribution. The LVDC distribution network is one of the emerging technologies taking advantage of the good qualities of power electronics and higher transmission capacity achieved in low voltage network by using DC instead of AC. [1] [2] Basic concept of LVDC network is shown on figure 1.

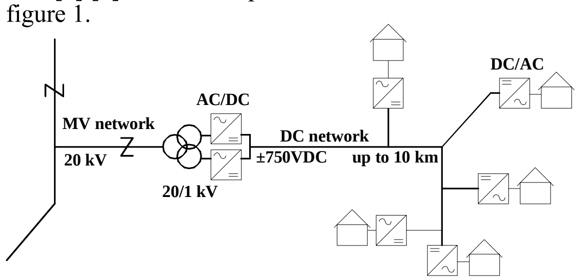

Figure 1. Basic concept of LVDC distribution network

LVDC network is based on power electronics. The front-end rectifier and inverter loads are sources of harmonics in the LVDC system. The front-end 3-phase thyristor rectifier, that is the economical solution for systems with directional power flow, will excite 300 Hz ripple to the DC voltage, when the frequency of the feeding network is 50 Hz. The voltage ripple lead also to the existence of 300 Hz currents in the DC network, later on referred as the 6^{th} harmonic current. The voltage transformation back to AC voltage at customer-end can be carried out either with 1-phase or 3-phase inverters. The 1-phase inverter will drain current from dc network with 100 Hz frequency, if the frequency of customer's AC supply is 50 Hz. The 3-phase inverter will drain pure direct current under balanced load. However, normally the load due to customer appliances will quite often be unbalanced between the phases. Hence, in practice, the current taken by the 3-phase inverter from the DC network also contains the 100 Hz component, later on referred as the 2^{nd} harmonic. Distorted current creates additional losses in the DC network. The harmonic contents of the current in the DC network depend on the size of installed capacitance. Putting more capacitance at the front-end of the DC network will reduce magnitude of 6^{th} harmonic. Equally, increasing the capacitance value in the customer-end of the network, at the inverters, will reduce the magnitude of the 2^{nd} harmonic currents in the network.

In rural distribution network, overhead lines in which are the typical medium voltage feeder structure, the customers experience annually remarkable amount of momentary interruptions due to autoreclosing functions of the feeder protection. It is typical that 50-70 % of the total number of momentary interruptions is due to the high speed autoreclosing (HSAR) function of the feeder protection, de-energized time of which is often round 0.4-0.5 seconds. Dimensioning the DC network capacitances to provide energy to the customer's loads during the HSARs can remarkably improve the supply quality.

The total capacitance of the DC network has to be divided between the front-end rectifier capacitance and customer-end inverter capacitance. In the selection of the rectifier and inverter capacitances, the voltage distortion, the network losses and the stability of the DC network are in main role. The need to supply energy during momentary interruptions impacts on the total magnitude of the capacitance. Also the impact of the rectifier and the inverter capacitor sizes into the fault currents in the DC network and thus into the operation of the protection system have to be considered. The trip limits of overcurrent protection devices can limit the capacitance values. A special case is the recharging current of the capacitors due to re-energizing the network after a blackout.

TECHNICAL APPROACH

Voltage ripple

Standard on low-voltage electrical installations [IEC60364] requires that DC voltage ripple (in the systems up to 1500VDC) is in 10% range of rated DC voltage.

DC capacitors on front-end rectifier

The front-end 3 phase six pulse rectifier produces 300Hz voltage ripple in DC network with

$$U_{ripple}^{rec} = \left(\sqrt{2} - \sqrt{\frac{3}{2}}\right) U_n \tag{1}$$

Where U_n is rectifier input voltage. For LVDC network $U_n = 562V$ and $U_{ripple}^{rec} = 106V$. For DC network with 750VDC nominal voltage level voltage ripple is out off standard range. In the case of the rectifier with capacitor filter and constant power load, using energy balance principle that discharged energy is equal to acquired energy, can be stated

$$U_{ripple}^{rec} \cdot C_{rec} = I_{dc} \cdot T_2 \tag{2}$$

Assuming that time T_2 is equal to half of the periodic time of the waveform

$$U_{p-p\,ripple}^{rec} = \frac{I_{dc}}{2 f_{ripple} C} = \frac{P}{2 f_{ripple} C U} \tag{3}$$

For the LVDC network with bipolar link the rectifier capacitors sizes can be determined for network rated power and voltage level

$$C_{rec\pm} = \frac{I_{dc}}{2 f_{ripple} U_{p-p\,ripple}^{rec}} = \frac{P_{DC\pm}}{2 f_{ripple} U_{p-p\,ripple}^{rec} U_{dc}} \tag{4}$$

For LVDC network with dc network nominal voltage $U_{dc} = 750VDC$, can be calculated:

$$C_{rec\pm} = 30\mu F/kW$$

DC capacitor on customer end

The size of the customer side capacitance (before customer inverter) is calculated using the energy balance equation as follows [3]:

The inverter output on fundamental frequency ω_1

$$v_{o1} = v_o = \sqrt{2} V_0 \sin(\omega_1 t) \tag{5}$$

The output current of inverter can be written

$$i_o = \sqrt{2} I_0 \sin(\omega_1 t - \phi) \tag{6}$$

The energy balance equation is

$$V_d i_d(t) = v_0(t) i_0(t) = \sqrt{2} V_0 \sin(\omega_1 t) \cdot \sqrt{2} I_0 \sin(\omega_1 t - \phi) \tag{7}$$

Therefore

$$i_d(t) = \frac{V_0 I_0}{V_d}\cos(\phi) - \frac{V_0 I_0}{V_d}\cos(2\omega_1 t - \phi) \tag{8}$$

$$i_d(t) = I_d - \frac{V_0 I_0}{V_d}\cos(2\omega_1 t - \phi) \tag{9}$$

Differential equation for the capacitor voltage is

$$C_{inv}\frac{dV_d}{dt} = I_d - i_d(t) \tag{10}$$

$$\frac{dV_d}{dt} = \frac{1}{C_{inv}}\frac{V_0 I_0}{V_d} cos(2\omega_1 t - \phi) \tag{11}$$

$$v_d = V_{DC} + \frac{1}{C_{inv}}\frac{V_0 I_0}{V_d}\frac{1}{2\omega_1}\sin(2\omega_1 t - \phi) = V_d + v_{ripple} \tag{12}$$

Minimum capacitance for the maximum allowed ripple is

$$C_{inv}^{min} = \frac{1}{v_{ripple}^{max}}\frac{P_0}{V_{DC}}\frac{1}{2\omega_1} \tag{13}$$

The minimum customer side DC capacitance on 1 phase inverter terminals (with dc network nominal voltage $U_{DC} = 750VDC$ and maximum acceptable voltage drop in DC network is 20%) is then

$$C_{1phase\ inv}^{min} = 44\mu F/kW$$

The 3-phase inverter dc -side current is a dc quantity in balanced load conditions [3]. Under unbalanced conditions, (rated current in one phase, zero in others) maximum power is one third of the rated power

$$P_0 = \frac{P_{3p}}{3} \tag{14}$$

According to equation (13)

$$C_{3phase\ inv}^{min} = 15\mu F/kW$$

Momentary interruptions

The voltage hold up time during MV supply interruption gives one more guideline for selecting the size of capacitors. The difference in the energy stored in the system capacitors in the beginning and in the end of the supply interruption is equal to the energy needed for load feed.

$$W_{stored} = \frac{1}{2}\cdot C_{network}\cdot\left(U_{dc,max}^2 - U_{dc,min}^2\right) \tag{15}$$

$$W_{feed} = P_{load}\cdot t \tag{16}$$

$$\frac{C_{network}\cdot\left(U_{dc,max}^2 - U_{dc,min}^2\right)}{2} = Pt \tag{17}$$

$$C_{network} = \frac{2Pt}{\left(U_{dc,max}^2 - U_{dc,min}^2\right)} \tag{18}$$

As stated in the introduction, remarkable improvement in supply quality can be achieved by reducing the number of HSARs seen by a customer. The interruption time in HSAR can be assumed to be round 0.5 s. Then if the minimum DC network voltage on the 3 phase inverter terminals is 650VDC [3], as is the case when the sine-triangle modulation is used in 3-phase inverters, the required network capacitance per load kW in DC network with 750 VDC nominal voltage becomes

$$C_{network} = 14\ \frac{mF}{kW\cdot s}$$

In Finland, elimination of each HSAR bring 0.55 €/kW savings for distribution company through the distribution business regulation model [4].

Maximum DC network capacitance

The current in DC network is uncontrolled. Therefore, after voltage sag etc., large amount of recharge current may flow to the DC network [5]. Maximum amount of recharge current should be restricted below the trip current of protection and current handling capacity of the rectifier. Maximum DC network capacitance as a function of maximum recharge current (neglecting resistances of feeding side) can be written using equation given by Pietilainen [6]

$$C_{rec}^{max} = \left(\frac{\Delta i^{max}}{\Delta v_{dc}}\right)^2 \cdot (L_{grid} + L_{trans}) \tag{19}$$

For 100kVA network, with nominal current $I_n = 145A$ with short-circuit current tripping set to $4\times I_n$

$$\Delta i^{max} = 580kA$$

Maximum DC network capacitance in this case

$$C_{rec}^{max} = 12mF$$

Recharge current restricts the maximum of DC capacitance when rectifier is uncontrolled. This restriction is removed if the DC network is fed with thyristor rectifier, where recharge current is limited by a firing angle control during voltage dips and interruptions.[5] Transient state fault current fed by the inverter capacitances increase the operation time of the DC network overcurrent protection devices placed on the AC side of the rectifiers. The transient state current fed by the inverter capacitances also have to be considered when selecting the operation principle of the overcurrent protection devices situated in front of the inverters. Directed overcurrent relays should be used to prevent false tripping or the transient current have to be kept under the instantaneous trip value.

The DC network stability condition

To analysis the system stability in the frequency domain, the LVDC distribution network model was created. DC network stability condition is the requirement for customer side DC capacitor size. [7]

$$C_{inv} > \frac{P_{cpl} \cdot (L_l + L_{dc})}{(U_{dc}^2) \cdot (R_l + R_{dc})} \tag{20}$$

For system with parameters: $R_{line} = 0.052\ \Omega$; $L_{line} = 0.36$ mH; $R_{dc} = 0.32\Omega$; $L_{dc} = 0.27$ mH; $U_{dc}^{min} = \frac{U_{dc}^{nom}}{2}$ next stability condition must satisfy

$$C_{inv}^{Up\ to\ MPP} >\approx 12\mu F/kW$$

Boundaries for the size of the system capacitors derived from the stability conditions are less then from dc voltage ripple requirements.

The DC network resonance

The DC network inductance and DC capacitors may cause resonance. If one of the harmonics corresponds with serial resonance frequency high resonance currents will flow in dc link. The damping factor of the serial resonance can be calculated in general as

$$\xi = \frac{R_{line}}{2}\sqrt{\frac{C}{L_{line}}} \tag{21}$$

Then capacitance for the critically damped system ($\xi = 1$) is

$$C_{SR}^{\xi} = \frac{4\xi^2 L_{line}}{{R_{line}}^2} \tag{22}$$

With 200 m of DC network with parameters $L_{line} = 0.058mH$, $R_{line} = 0.382\Omega$, the DC capacitance is $C_{SR}^{(\xi=1)} = 1590uF$; With 1km of DC network with parameters: $L_{line} = 0.28mH$, $R_{line} = 0.86\Omega$, the DC capacitance is $C_{SR}^{(\xi=1)} = 1487uF$. Damping of oscillations in the DC network may lead to bigger DC capacitance than required by the voltage ripple limits.

Harmonic interaction analysis using bode diagrams

In order to validate the selections, made by analytical equations, the LVDC network resonances and harmonic amplification are examined in frequency domain. To determinate propagation of the front-end rectifier exited harmonic, system is analysed using system transfer function from source to load [7] and bode diagrams (Figures 2, 3). Selection of small size customer side capacitance (250uF) will amplify rectifier exited harmonic (300Hz) by 3.5 times. Bigger size capacitance (1600uF) will remove amplification of rectifier exited harmonic. If there is a source of 100Hz harmonic close to the front-end rectifier in the system under investigation, exited harmonic can be amplified in dc network. Amplification depends on rectifier side DC capacitor size.

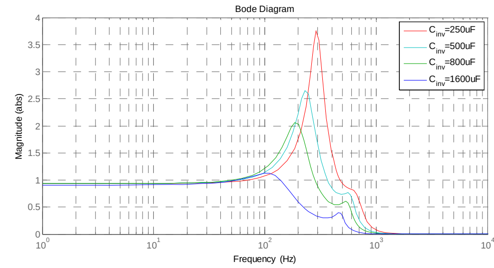

Figure 2. System frequency response. Inverter DC capacitance is varied; Rectifier DC capacitance is fixed at 500μF.

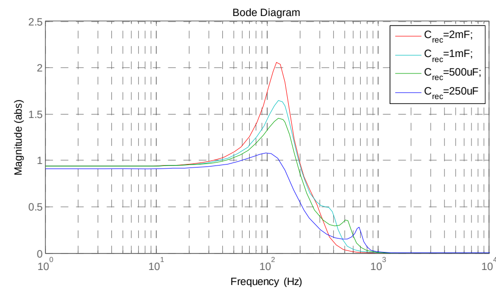

Figure 3. System frequency response. Rectifier capacitance is varied; Inverter capacitance is fixed at 1600μF.

To determinate propagation of inverter load exited harmonic, system is analysed using system transfer function from load to source [7] and bode diagrams (figure 4).

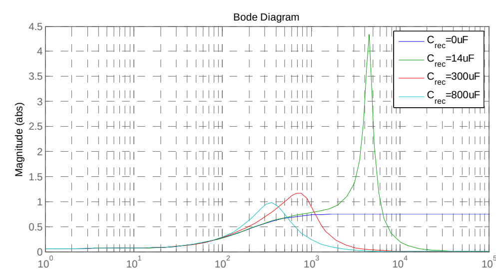

Figure 4. System frequency response.

Small size of the rectifier capacitance can cause possible amplification of the high switching frequency harmonics. The selection of DC network capacitances sizes can be verified using system model and bode plots. Capacitor sizes may be corrected to avoid resonances in the system and reduce amplification of the harmonics in network. Because frequency domain analysis is based on simplified model of the network, for complicated DC network creating a detailed model may be a problem. Thus analysis in electromagnetic transient simulation software environment is necessary.

Simulation of the LVDC network

For time domain analysis a LVDC power distribution system was modelled using electromagnetic transient simulation software EMTDC/PSCAD. Time domain simulations provide voltage and current waveforms and they harmonic contents depending on system configuration and system state.

Verification of the PSCAD/EMTDC model

The LVDC prototype model is supplying 1-phase inverter with 5 kW load. The model is verified by measurements with corresponding real network setup in the laboratory (Figure 5). More on the verification is presented in [8]

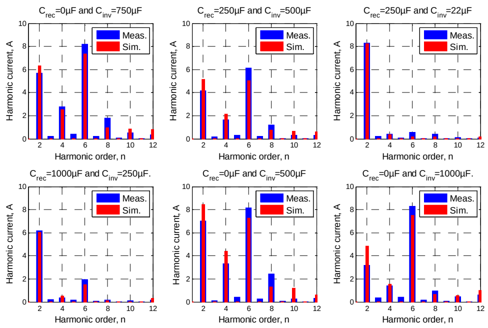

Figure 5. Harmonic current spectrums in DC network (measured and simulated)

The model gives reliable results for harmonic content of DC network currents. The uncertainty in the supply network parameters gives deviation between simulation and measurement results in cases where there is no capacitance on the rectifier DC terminals.

Power Losses in LVDC network

The model of the LVDC network with 20/0.562/0.562kV 0.1MVA transformer, bipolar DC network (0.9km and 1.4km AXMK 3x95) and 3 phase inverters (40kVA), under unbalanced load conditions (13kW, 7.5kW, 6kW per phase), on each pole is created in PSCAD environment for investigation of the power losses. The peak load condition of the LVDC network is simulated. The effect of the distribution and size of the DC network capacitances on the power losses presented in (Table 1).

Table 1. Power losses in the LVDC network.

Name	CASE 1	CASE 2	CASE 3	CASE 4
Capacitors	Rated	Oversized	Undersized	Undersized
C_{rec}	1.2mF	2.4mF	600µF	1.2mF
C_{inv}	720µF	1.4mF	720µF	360µF
Power losses in kW				
$P^{h}_{dc\,network}$	0.485	0.11	1.51	0.54
$P^{h}_{transformer}$	0.074	0.072	0.067	0.081
$P^{dc}_{dc\,network}$	1.31	1.31	1.36	1.31
$P^{50Hz}_{transformer}$	0.31	0.325	0.37	0.355
Total	2.179	1.81	3.3	2.28

The capacitor placed on the DC terminals of a converter affect directly on the harmonic currents it excites. Consequently, the power losses due to current distortion decrease quadratic proportionally to the decrease of harmonic currents, as can be seen when comparing simulation cases 1 and 2.

Economical approach

The increase of capacitance in the DC network to reduce the losses is justified, if the reduction in the costs of losses is higher than the price of added capacitance. This can be expressed

$$\left(\Delta P^{\mathrm{h}}_{\mathrm{dc\ network}} + \Delta P^{\mathrm{h}}_{\mathrm{transformer}}\right) \cdot price_{\mathrm{losses}} > \Delta Cost_{\mathrm{capacitor}}$$

where $price_{\mathrm{losses}}$ is the unit price of power losses over the utilisation period of the network and $\Delta Cost_{\mathrm{capacitor}}$ is the costs due to increasing the capacitance. For instance, if the price of losses is 0.05 €/kWh, peak operation time of losses 1000 h and utilisation period 40 a, the unit price for power losses over the utilisation period becomes 857.95 €/kW. Thus, the costs of doubling the size of capacitors from the values used in simulation case 1 to the values used in simulation case 2 can be in maximum 323.45 € during the utilisation period regardless of the lifetime of the capacitors.

CONCLUSION

The guidelines, presented in the paper, provide requirements and boundaries for the LVDC network DC capacitor sizes. The minimum size of the DC capacitances for the front-end rectifier and customer-end inverter are determined from voltage ripple requirements. DC network stability requirements, DC resonances, harmonic amplification in DC network, power supply during momentary interruption and maximum recharge current are setting boundaries on dimensioning of capacitance. The LVDC network frequency-domain analysis and time domain simulations allow correction of capacitor sizes to avoid resonance issues and amplification of the harmonics in the DC network. The harmonic power losses are decreasing quadratic proportionally to increase of the capacitance size. Economical profitability of reducing power losses by increasing capacitance size is discussed.

REFERENCES

[1] J. Lassila, T. Kaipia, V. Voutilainen, J. Haakana, K. Koivuranta, and J. Partanen, “Potential of power electronics in electicity distribution systems,” *CIRED Seminar 2008: SmartGrids for Distribution*, 2008.

[2] T. Kaipia, P. Salonen, J. Lassila, and J. Partanen, “Possibilities of the low voltage dc distribution systems,” *NORDAC*, 2006, pp. 1-10.

[3] N. Mohan, T.M. Undeland, and W.P. Robbins, *Power Electronics: Converters, Applications, and Design*, Wiley, 2002.

[4] The Finnish Electricity Market Authority, *Guidelines for assessing reasonableness in pricing of electricity distribution network operations for 2008-2011*, 2007.

[5] P. Nuutinen, A. Lana, T. Kaipia, and P. Silventoinen, “START-UP OF THE LVDC DISTRIBUTION NETWORK,” *CIRED 2011 conference*, 2011.

[6] K. Pietilainen, L. Harnefors, a Petersson, and H.-P. Nee, “DC-Link Stabilization and Voltage Sag Ride-Through of Inverter Drives,” *IEEE Transactions on Industrial Electronics*, vol. 53, Jun. 2006, pp. 1261-1268.

[7] A. Lana, T. Lindh, and J. Partanen, “LVDC Power Distribution System Concept: System Stability,” *Power Systems Computation Conference*, 2011.

[8] T. Vornanen, A. Mäkinen, P. Järventausta, A. Lana, T. Kaipia, and P. Nuutinen, “PSCAD MODELING AND SIMULATION OF LVDC DISTRIBUTION NETWORKS,” *NORDAC 2009 conference*, 2009.