START-UP OF THE LVDC DISTRIBUTION NETWORK

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ABSTRACT

In a Low-Voltage Direct Current (LVDC) distribution network, the customer-end inverter requires a capacitance, which is directly connected to the DC network. This capacitance, which depends on the structure of the network and the number of customers, is always notably higher compared with a traditional AC network. When the LVDC network is started up, the capacitances require charging current, which, with the network inductance, can cause an overvoltage at the customer. In this paper, the start-up of the LVDC network is studied.

INTRODUCTION

In this paper, the power transmission between a customer and a medium-voltage branch line is implemented by using direct current. The drivers for this type of a distribution system are, for example, increased power transmission capacity, customer-end voltage quality and reliability [1], [2]. In most of the LVDC networks, the power transmission in the DC link can be unidirectional. Because the nominal voltage level in the DC link is 750 V and the minimum required voltage level is 566 V with the three-phase and 325 V with the single-phase CEI (Customer-End Inverter), there is no need to keep the DC voltage at a constant level. Actually, an advantage of the LVDC system is that the customer-end voltage can be kept at the nominal level even though the voltage in the MV network varies. Because the LVDC system itself places no requirements for a controlled rectifier, it does not have to be controlled.

However, every CEI requires a capacitor in the intermediate circuit, which increases the capacitance of the DC network. The total capacitance of the entire DC network is always significantly higher compared with the traditional AC network. The capacitance also depends on the number of customers and the maximum power of the inverter. When the network is started up after a long interruption, the capacitor charging may take several seconds. But when a high-speed auto reclosing (HSAR) occurs in the AC network, the voltage in the MV network drops to zero during the reclosing, and the capacitors have to be charged quickly; the duration of the interruption cannot be longer in the LVDC system than it is today.

NETWORK CAPACITANCE

If the target is to decrease the start-up time, the start-up current has to be increased. When the current is increased, the energy in the network inductance increases. This can cause the DC voltage at the customer to exceed the maximum allowable level during charging, which can cause equipment failures. The voltage level can also vary in different parts of the network, which results from the various customer-end capacitors and the structure of the network. The maximum allowable voltage is 10 % higher than the nominal value, which is 750 V in this paper. The studied network is presented in Fig. 1.

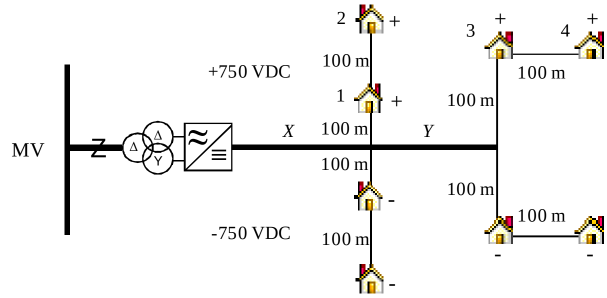

Fig. 1. Bipolar LVDC network with four customers connected to +750 VDC and four customers to -750 VDC.

Capacitor dimensioning

Harmonic sources in the LVDC system are the front-end rectifier and the CEIs. To guarantee the power quality in the LVDC network, there have to be capacitors located both at the rectifier and in the CEI side. The standard SFS 50160 [3] limits the maximum voltage ripple in the DC network to 10 % of the nominal voltage, which defines the minimum size of the network capacitances. The sizes also depend on the nominal power of CEIs and whether they are single-phase or three-phase ones. The capacitor values used in this paper can be calculated from the *C/P* values: C_{rec} is the rectifier side, $C_{1-\mathrm{phase}}^{100\mathrm{Hz}}$ is the single-phase CEI side and $C_{3-\mathrm{phase}}^{100\mathrm{Hz}}$ is the three-phase CEI side capacitance (30 μF/kW, 44 μF/kW, and 18 μF/kW, respectively). [4]

RLC CIRCUIT STEP RESPONSE

When minimizing the start-up time, the characteristics of the network have to be studied. The LVDC network with one customer is an *RLC* circuit, and the start-up behaviour can be studied as a step response of the circuit presented in Fig. 2. In this circuit, R is a sum of the transformer and cable resistance, L is a sum of the transformer and the cable inductance and C is the sum of the customer-end and rectifier-end capacitance. The capacitance of the cable is neglected in the calculations and simulations. The rectifier is replaced with a DC source in calculations.

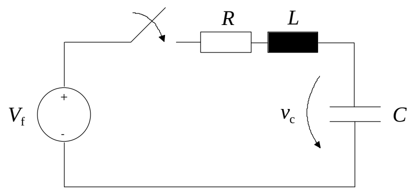

Fig. 2. *RLC* circuit used in the calculation.

The equation for the capacitor voltage v_c can be solved as follows [5]. The characteristic equation of the circuit is

$$s^2 + \frac{R}{L}s + \frac{1}{LC} = 0\,. \tag{1}$$

The roots of the characteristic equation (1) are

$$s_{1,2} = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2} \tag{2}$$

where α is the neper frequency and ω_0 is the resonant radian frequency of the circuit.

$$\alpha = \frac{R}{2L}\,\text{rad/s} \tag{3}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}\,\text{rad/s} \tag{4}$$

During the start-up, the voltage of the capacitor will overshoot only if the circuit is underdamped, that is, $\omega_0^2 > \alpha^2$. The equation for the capacitor voltage v_c in the underdamped circuit is

$$v_c(t) = (V_f + B_1^{'} e^{-\alpha t}\cos\omega_d t + B_2^{'} e^{-\alpha t}\sin\omega_d t) \quad \text{V}, \tag{5}$$

where t is the time, V_f is the DC link voltage, $B_1^{'}$ and $B_2^{'}$ are real constants and ω_d = is the damped radian frequency

$$\omega_d = \sqrt{\omega_0^2 - \alpha^2}\,. \tag{6}$$

The value of the capacitor voltage is at maximum when $dv_c/dt = 0$. The diodes of the rectifier keep the capacitor voltage at the maximum level and prevent it from oscillating. The capacitor voltage depends on R, L and C, which all change when the structure of the network changes. The voltage of the capacitor v_c as a function of cable length s is calculated, and the result is presented in Fig. 3. The solid curve is calculated with a star-connected and dotted curve with a delta-connected 50 kVA transformer parameters [6]. The selected cable is AXMK 4x25 [7]. The capacitance value C = 768 µF is calculated from the three-phase CEI capacitance value, because then the capacitance is lower and the damping of the circuit is smaller. As a result, higher overvoltages are possible. This, of course, is a theoretical case, and there is seldom a LVDC network with only one customer.

As can be seen in Fig. 3, the magnitude of the overvoltage depends on the length of the cable and also on the vector group of the transformer. When the cable resistance increases, the damping of the system increases, which in turn has an effect on the voltage overshoot. The rectifier current is the same with both vector groups, because the relative per unit short-circuit impedance of both the transformer secondaries should be equal. However, the voltage is lower because the winding resistance is higher in the delta-connected secondary.

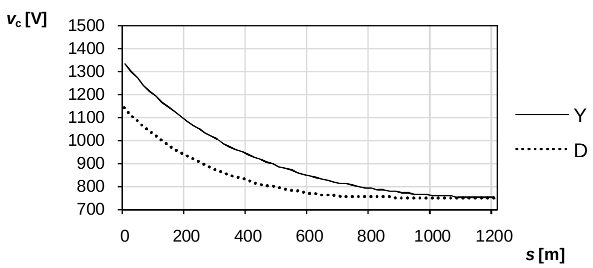

Fig. 3. Capacitor voltage after start-up in the star and delta-connected network as a function of cable length.

When a rectifier and more customers are added to the network, the start-up cannot be covered with a larger single capacitor and a larger transformer. The capacitors have to be connected in parallel, and the distances between customers have to be taken into account. Moreover, there are customers with different powers in the network, which affects the size of the capacitance and the cross-sections of the cable. Charging with the 750 V DC source represents the worst case. With a three-phase rectifier, the voltage step is more like a slope, which affects the charging current. Because the studied system is more complicated, the start-up is simulated by Simplorer 8 simulation software.

SIMULATIONS AND ANALYSIS

The network used in the simulations is presented in Fig. 1. The cross-sections of the cable are selected based on a techno-economical study [7],[8]. The delta-connected transformer secondary has always a higher resistance, which increases the damping of the circuit. As a result, the overvoltages and the currents are always lower than they are in the star-connected side. Therefore, the simulations are made only with the star-connected side of the network. In the simulations, the voltage differences between the customers 1–2 and 3–4 are not significant, and thus, the capacitors are combined and denoted as C_x and C_y. The simulation parameters are presented in Table 1. S_n is the transformer nominal power, X and Y are the cable lengths in Fig. 1 and P_x and P_y are the power levels from which the capacitor values C_x and C_y are calculated. The parameters of the transformer are typical C-C' class values [6].

Analysis

In simulation 1, the network is simulated with the capacitances that represent four 16 kVA customers. When the distance between the first capacitor and the rectifier is short, an overvoltage can be detected. When the distance between the rectifier and the capacitor C_x is increased in simulation 2, the overshoot decreases. This results from the increased cable length resistance, which has an effect on the damping of the system. If the voltage is considered, the network can be charged with a diode bridge rectifier. When the values of C_x and C_y are increased in simulation 3, the voltage behaviour is almost the same as in simulation 1, but the value of the current has doubled. The higher capacitance increases the damping, but at the same time, the changed transformer and cable parameters have an opposite effect. If only capacitances are changed, the behaviour is more similar to simulation 2.

In simulation 4, the cable and transformer parameters are the same as in simulation 3, but the distances are changed and C_y has a lower value. This represents a situation where there is only a one small customer at the end of the network, but the cable is selected for possible higher loads in the future. As can be seen, the overvoltage is not significantly higher than in simulations 1 and 3, even though the distance between the rectifier and C_x is very short. This shows that the capacitance, which is close to the rectifier, has the main effect on the system behaviour.

Even though the overvoltage in simulations 1, 3 and 4 could be accepted, the charging current is too high for the components of the network. Although the rectifier is able to supply short-time charging currents multiple times its nominal current [9], commercial protection devices cannot be adjusted for currents this high. This causes false trips in the rectifier and the customer-side devices. Also the maximum current of the capacitance may be exceeded. When a thyristor bridge rectifier is used in simulation 5, the startup current can be controlled and there is no voltage overshoot. The parameters of the circuit are the same as in simulation 3, but the current decreases to one-fifth of the original value. With the thyristor bridge, it is possible to vary the start-up time, which is needed if the start-up of the network is wanted to be optimized in different situations.

Start-up after HSAR

The CEIs will feed loads as long as the voltage in the DC network is higher than the single-phase or three-phase peak value. The standard [3] allows a 10 % customer-end AC voltage drop, which extends the CEI operating time during the HSAR, because the voltage of the capacitor decreases more before the CEI undervoltage shutdown. The operating time depends on the current power level of the CEI. For example, a 16 kVA three-phase CEI operates on the capacitor power 10 ms at full power, but at the 2 kW power the time is extended to 100 ms. The start-up after the HSAR differs from the initial start-up because there is already voltage in the network. This voltage is roughly 510 V with the three-phase CEIs in the network and 293 V when there are only single-phase CEIs in the network. The total dead time during the HSAR depends on the size of the capacitor, the current CEI power and the charging time of the customer. If there is a minimum amount of capacitance and the power is high, the HSAR effect is always longer than it is today. It is possible to start the CEI while the rectifier charges up the capacitors and the capacitor voltage is sufficient. This shortens the dead time. However, the current of the rectifier in this point has to be lower than the maximum charging current, even though there are many CEIs operating, all of them at a different power level. The voltage level at which the CEIs start has to be defined appropriately so that the maximum current of the rectifier is not exceeded. The voltage loss in the DC cable has also to be taken into account to prevent the negative resistance phenomena in the cable.

Customer-end power storages

It is possible to use power storages during the HSAR. These storages contain multiple times the energy compared with the CEI or the rectifier-side capacitors. The storages can be dimensioned such that they are capable of supplying a full-power customer during the HSAR. On the other hand, the storages can contain more energy, in which case the power supply of the customer is secured for a longer period. In every case, these storages require controlled charging, and their charging times are notably longer compared with the network start-up time. Consequently, they do not have to be taken into account when considering the start-up of the LVDC network.

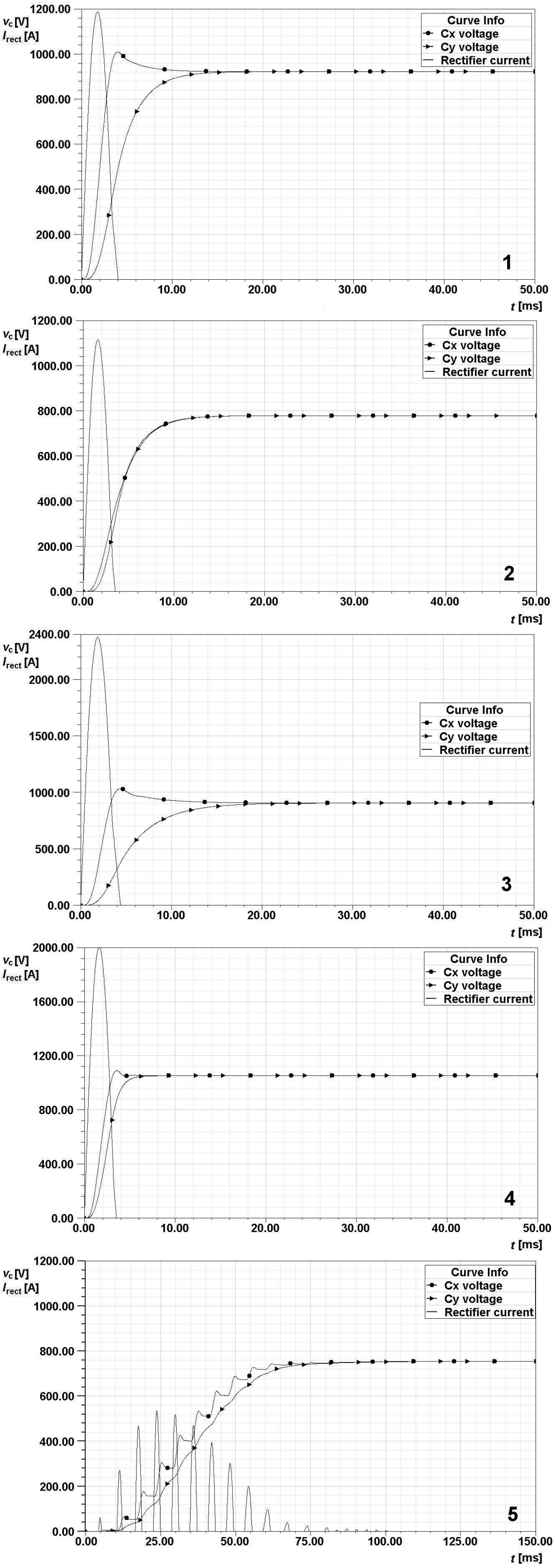

Fig. 4. Simulated capacitor voltages and rectifier currents.

Table 1. Simulation parameters. # represents the simulation number.

#	S_n [kVA]	X [m]	Y [m]	P_x [kW]	P_y [kW]
1	100	200	2000	32	32
2	100	2000	200	32	32
3	200	200	2000	70	70
4	200	50	2000	70	16
5	200	200	2000	70	70

CONCLUSIONS

In the start-up of the LVDC network, the network capacitance influences the start-up behavior. The capacitances take high charging currents, and the network inductance produces overvoltages. The parameters of the network change when the structure of the network is changed. Therefore, every network has to be studied individually if an optimal start-up behavior is desired in the HSAR. This leads to a situation where the diode bridge rectifier can be used only in some individual cases, while in most cases, the current and voltage rises excessively. With the thyristor bridge rectifier, the start-up currents can be controlled. It is also possible to use different control parameters in different networks or on different occasions, which makes the thyristor bridge a better choice for this application.

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