DISTRIBUTED GENERATION IN DC DISTRIBUTION SYSTEM

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ABSTRACT

Nowadays electricity distribution networks construct mainly of the three-phase AC systems. Consumer voltage in traditional distribution system is 230/400 V and the nominal frequency in Europe is 50 Hz. Expectations both on electricity distribution techniques and the distribution business are growing. One of the leading themes in developing low voltage DC-distribution system is to find a profitable solution to enhance the reliability of electricity distribution cost effectively. Low voltage DC-system also enables connecting small-scale distributed generation (DG) directly to the network.

In the paper the impact of DG in low voltage DC-system's to network structure and power quality is discussed. Also the overall reliability and power quality effects and possibilities of DC systems are approached. The paper presents example calculations performed on a network constituting of almost 1000 km of medium voltage lines. In addition also the structural impact and cost effect of the low voltage DC-system to the example network is considered in the paper.

INTRODUCTION

The European Union (EU) low voltage directive (LVD 72/23/EEC) [1] defines the boundaries for the low voltage (LV) levels used in public distribution systems. According to the directive any electrical equipment designed to be used with defined voltage ratings is a low voltage instrument. The LVD 73/23/EEC covers equipment designed for use with a voltage rating between 50-1000 V AC and between 75-1500 V DC.

DC-distribution enables the improvement of the customer's electricity quality beyond today's level with lower costs compared to AC systems. By applying DC low voltage system, the length and number of branches in the (MV) medium voltage (10…30 kV) network can be diminished and whole medium voltage network shortened. With this the number of possible fault situations in medium voltage network, affecting hundreds of customers, can be reduced and the quality of distribution increases. Simultaneously customer's voltage quality can be increased. Application of the DC system reduces voltage fluctuations at the customer's end and the operating voltage can be kept nearly constant. However, as the application of the proposed DC system adds the number of network components it might add the possibility of inner system faults.

LOW VOLTAGE DC-DISTRIBUTION

DC distribution system constructs of a DC connection that replaces both the MV branch line and traditional low voltage network. In this case the LV transforming district contains only a wide DC connection between MV main line and contact points of the customers. The power is transferred with DC-link all the way to customers where the DC voltage is inverted back to AC voltage. Because of inverting DC voltage direct to customers operating voltage there is no need for additional distribution transformers inside the transforming district like in the MV/1/0.4 kV AC-system. In Fig. 1 the principle of the proposed DC-distribution system with comparison of system structure to the traditional AC systems is presented.

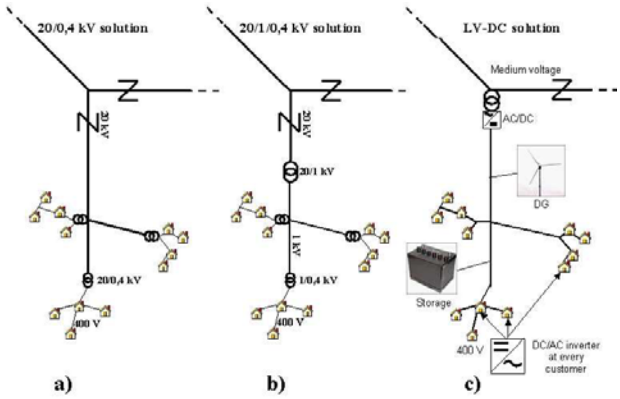

Fig. 1. Feeding a customer group a) with the 20/0.4 kV solution, b) with the 20/1/0.4 kV solution, c) with the proposed DC-distribution system.

In order to maintain the DC-system as a LV-system it has to be fed with LV-AC-network. For keeping the required rectifiers and power electronics feeding the DC-system simple without reducing the DC voltage level too much from the 1500 V, it is reasonable to feed the LV-DC-system with 1 kV LV-AC-system. With this kind of arrangement the nominal voltage of the DC-link is 1440 V. This also enables, that the same MV/1 kV transformer than in MV/1/0.4 kV AC-distribution systems. The AC voltage is rectified to DC voltage right after the transformer.

Application of the DC system reduces voltage fluctuations at the customer's end and the operating voltage can be kept nearly constant. The customer's operating voltage can be produced from wide range of DC voltages as long as the voltage of the DC link is over 560 V, voltage needed by the 12-pulse inverter or over 800 V for 6-pulse inverter to produce 400 V three-phased-supply. This means that the voltage drop and voltage dips resulted from different parts of the network can be repaired with active inverter control if DC voltage in inverter poles is greater than required minimum voltage to produce customer's operation voltage. The only customer disruption in DC distribution is voltage break if DC voltage falls under the required minimum DC voltage. In the fault situations the bipolar distribution system can also be used in half capacity if the loads in this case do not exceed capacity limits of the system components.

Batteries and capacitors connected to the DC-link can be used as emergency power supplies during long and short the outages in medium voltage network if no DG is connected to DC network. For short-term interruptions, like auto reclosures, the power supplied by capacitors installed for example in converters is enough to maintain constant voltage at customer. For longer time interruption in medium voltage levels DG or batteries connected to the DC-link are required.

The LV-DC-network provides an ideal connection to the small scale DG as the power flows in the network as well as production and loads can be actively controlled. Many production techniques like fuel cells, solar panels and wind turbines can be connected to the DC-network with quite simple power electronics. For instance, a wind turbine with AC-generator is today connected to the AC-network through AC/DC/AC frequency converter. In the case of DC-distribution the second AC level is not needed at every generator as the energy is either consumed locally by the loads at the DC-network or transmitted to the MV-network through centralized DC/AC converter.

The disadvantages of DC systems occur mainly in the power electronic devices. The lifetimes of electronic devices are shorter than in the case of the traditional network components. Power electronic devices also increase losses and produces voltage harmonics to the network. Harmonics filtration has to be used which increases the total costs. As the application of the proposed DC system adds the number of network components and also mixes AC and DC distribution, the distribution system in total becomes considerably more complex than traditionally. This makes the design and operation processes complicated.

APPLICATION POTENTIAL STUDY

The effects of the LV-DC-system to the structure of the distribution networks can be studied by analysing the application potential of the DC-system at a distribution network. On the basis of the techno-economic studies presented in [2], [3], the LV-DC-system can be used to replace at least those MV-branch lines of which load is less than 300 kW. Because of the costs of the power electronic devices the replacement of low load branches is not economical, but this result depends on the network topology, locations of customers and their power demand as well as the deviation to different customer groups. The economical potential is also dependent on the characteristics of the MV-feeder in which the LV-DC-district is connected to. Because the economical lower limit of the application of the LV-DC-system is very case specific a safe limit for the minimum power have to be determined. In the presented example calculations the limit is assumed to be 50 kW and so the application range of the LV-DC-system as a replacement of a MV-branch line is 50 – 300 kW.

The application potential of the LV-DC-system and harsh approximation of its impacts to the reliability can be defined by mapping the possible targets from the network. At this point only the MV-network is considered in the analysis and the benefits achieved by replacing the LV-AC-network with the LV-DC-system have not been taken into account. The application potential of the LV-DC-system based on the mentioned application range has been determined in actual MV-network.

The study is a typical rural area network from astern Finland of which length is round 1000 km. The network consists of seven 110/20 kV primary substations and supplies 165 GWh energy to approximately 14 000 customers. The structure of the MV-network is mostly radial overhead line network. Only interconnections between primary substations and few long feeders have backup connections. The network was divided into three parts in order to find out the possible LV-DC-targets. About 40 % of the MV-lines are so called main or interconnection lines between primary substations or other feeders and can not be replaced with the LV-DC-system. Rest of the lines (60%) are branch lines, of which 29 % are low-loaded branches (<50 kW) and the remaining 31 % branches replaceable with the LV-DC-system (50-300 kW).

As the reliability of the MV-network is related to its length the amount of faults caused by the MV-network reduces accordingly as the length of the network reduces. This increases the reliability of the distribution and remarkable cost savings in outage costs can be achieved. Also the capital costs of the network reduce, as the LV-components used in the LV-DC-system are inexpensive compared to MV-components. The economical benefit is however very case specific and far reaching generalisations can not be made on the basis of simple analysis.

As the distribution system becomes more complex and the number of components in the system increases there are also more possible targets for inner system faults compared to simpler traditional system. However, these faults affect only to the customers located in the DC distribution district. The harm caused by a DC fault is quite small compared to the situation of a fault incidence on a medium voltage line in which the fault impacts to all the customers connected to the feeder and can also be seen by customers on other feeders connected to same primary substation with the faulted feeder. From this point of view the application of the DC system, which replaces a part of the medium voltage network, reduces the average number of outages affecting a customer and so reduces the system average interruption frequency (SAIFI).

POWER QUALITY IN DC-DISTRIBUTION

The quality of the voltage for the public distribution networks is regulated by the European Standard EN 50160. This standard establishes all the admitted characteristics of the distributed voltage, their limits and the criteria for their evaluation [4]. They are:

- voltage variation: slow variation of the network voltage due to the load changing;
- fast voltage variation: single fast variation between two consecutive levels with defined but not specified duration. It can be caused by switching of the circuit brakes or by DG insertion.
- voltage fluctuation (flicker): cyclical variation of the voltage with lower frequency than the mains net frequency. Fluctuations can cause variations of luminance of the lamps with called annoying visual effect flicker;
- interruption: voltage value less than 1% of the nominal one;
- programmed interruption: interruption for programmed work;
- accidental interruption: interruption caused from transitory breakdowns; in can be:
  - long for duration > 3 min
  - short for duration until 3 min
- voltage sag: voltage value in the range of 1% to 90% of the nominal one with a duration between 10 ms and 1 s
- temporary overvoltage at mains frequency: duration of the overvoltage relatively long generally due to ground fault of the MV/LV transformer;
- transitory voltage swell: overvoltage with short duration (some milliseconds) due generally to lightning;
- harmonic voltages: voltages with multiple frequencies of fundamental ones due to non linear loads (static converters etc.);
- voltage unbalance: difference between the line voltages and/or phase angles (negative sequence component) due to unbalance loads

These definitions are related to the usual ac networks, but some concepts are valid also for dc network, while others have to be adapted for the examined case. The main differences regard to the following topics.

Fast voltage variations
Also in dc networks fast voltage variations can be determined by sudden load or DG connection/disconnection. Due to the presence of bulk capacitors in dc section, these variations are generally less rapid than those can occur in ac lines [5].

Fluctuations of voltage
In dc systems it is not possible to define an "interharmonic" because there is not any main frequency. So the definition Standard EN 50160 can therefore be adapted as follow: "a voltage fluctuation is a cyclical variation of the voltage with a frequency that can cause luminance variations of the lamps with annoying visual effect called flicker". With this definition it is important to adopt the same measures used in the ac mains for the flicker reduction especially around the frequency of 8.8 Hz. These fluctuations can be caused by cyclical variation of the dc load (i.e. motorcompressor), or by the variations of the injected power coming from renewable energy generator connected to the dc system. They cannot be generated by interharmonics as in ac network [6].

Interruptions
The dc system is connected to the ac one by means of interface converters that realize the ac/dc conversion. They can be diode bridges for unidirectional power flow, or IGBT bridges if reverse power flow is needed. These converters create a decoupling between ac and dc systems, therefore the dc section can still work during ac interruptions if storage systems or other generators (i.e. diesel genset) are inserted. This is an advantage for the dc systems especially where a high power quality level is required.

Voltage sags
Similar consideration can be done in the presence of voltage sags incoming from ac mains. Few deep sags can be compensated by the bulk capacitors used for voltage levelling, while for deeper sags suitable storage systems are needed. In any case the compensation devices are simpler and more reliable than in the ac systems.

Transitory overvoltages
The transitory voltage swells are essentially due to lightning that can induce in the dc lines dangerous e.m.f. The presence of the bulk levelling capacitors can reduce this phenomenon. In fact, these capacitances tend to keep constant the dc voltage of the systems in which they are inserted.

Harmonic voltages
Harmonic components in the dc voltage can occur as a result of ac voltage unbalance (in the next) or single phase/unbalanced load connected to the dc/ac inverters used for the final ac distribution. The current unbalance introduces a negative current sequence that causes power fluctuation at 100 Hz in 50 Hz European electric system. Power fluctuation causes voltage fluctuation if small levelling capacitance are used. This phenomenon is very narrow for the usual unbalance level in distribution networks.

Voltage unbalance
Voltage unbalance in ac systems are caused by load unbalance or single/double phase to ground faults. In the first case they can be limited with a suitable short circuit level for the connection point of the unbalance load, or with a uniform distribution of the single-phase load among the three line conductors. Instead, a line to ground fault have to be cleared by the protection system. Therefore the voltage unbalances that can take place in distribution network are usually neglected, but they can be relevant where the mains grid has a weak short circuit level. For example this is the case of rural areas characterized by few and long distribution lines.
In order to evaluate the effects of voltage unbalance on dc network, some simulations have been carried out.
The rms voltage values of the simulated system and represented in figure 2, are the following:

- V_1 = 230 V;
- V_2 = 194 V;
- V_3 = 194 V.

By applying the Fortescue transformation it is possible to obtain the three sequence components: zero, direct and negative:

- V_0 = 11,8 V;
- V_d = 206 V;
- V_i = 11,8 V.

Therefore, the simulated unbalance level, defined as the ratio between negative and direct components, is equal to 5.71%.

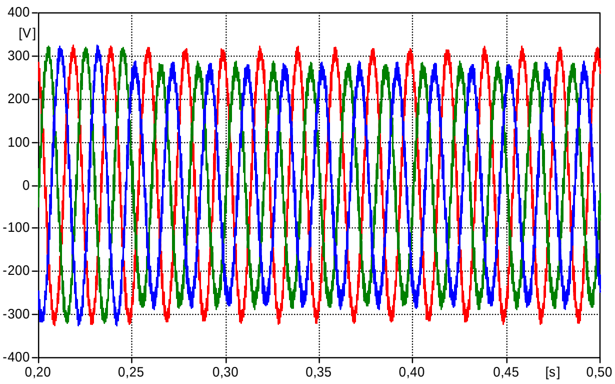

Fig. 2 Voltage unbalance of simulated ac mains grid.

As previously said, the consequence of the negative component of the ac voltage is a 100 Hz voltage harmonic in the dc section (figure 3), but if suitable levelling capacitor are installed, this fluctuation can be neglected. The same effect can occur in the load supplied by the dc/ac inverter is not equal on the three line conductors.

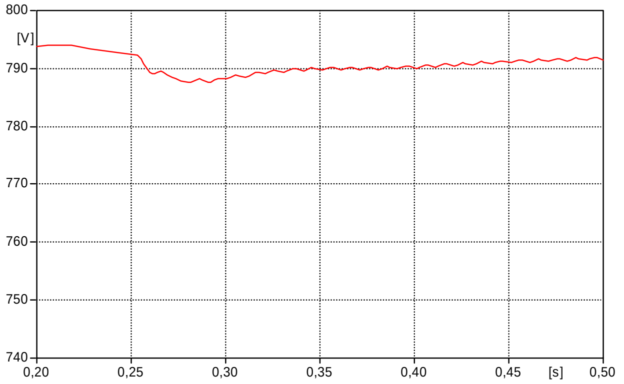

Fig. 3 Dc voltage fluctuation at 100 Hz following the unbalance voltage in the ac mains.

CONCLUSIONS

The application of the DC system, which replaces a part of the medium voltage network, reduces the average number of outages affecting a customer and so reduces the system average interruption frequency (SAIFI). The presence of storage systems and the use of IGBT AC/DC converters can significantly improve the power quality in the DC section.

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