COMMISSIONING INSPECTION OF AN LVDC DISTRIBUTION NETWORK

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ABSTRACT

A low-voltage distribution network today is based on three-phase AC system. In some cases, it can be replaced with an LVDC (Low-Voltage Direct Current) distribution network. Because the LVDC distribution technology requires practical studies, a real-network research platform has been introduced. The goal of the setup is to combine the requirements of the fully functional LVDC system and a flexible research platform. A commissioning inspection has to be performed when the LVDC distribution network is implemented in public network and in this paper, the inspection procedure for the LVDC real-network research platform is discussed. The commissioning inspection defined in the standard SFS 6000-6 is studied and the suitability of the procedure for the LVDC distribution network is discussed. Also, additional tests are introduced to ensure person safety, equipment safety, and proper functioning of the system.

INTRODUCTION

The LVDC distribution network could replace the present-day 400 V low voltage AC network and lateral parts of the medium voltage network in certain parts of the utility network. The possibility to use up to 1.5 kV DC voltage and power electronics instead of the maximum 1 kV AC voltage and traditional transformers increase the technical performance of the low voltage distribution [1], [2]. LVDC distribution provides improved customer-end power quality and supply security, improves the economy of the power distribution, constitutes intelligent platform for future SmartGrid functions, and improves the connectivity of DG and energy storages. The system basically consists of a rectifier, DC cable, and Customer-End Inverters (CEI). Principled structure of the LVDC distribution with DG and energy storages is presented in Fig. 1.

Real-Network Research Platform

To fully enable practical studies on LVDC distribution, a real-network research platform has been introduced. The goal of the setup is to combine the requirements of the fully functional LVDC system and a flexible research platform. From the converter technology perspective, the power and control electronics has to enable verification of different control algorithms, protection methods, and converter structures. Also, the operation of the converters in real load and weather conditions is one of the drivers. The real-network research platform is discussed in more detail in [3] and converter design in [4].

Existing 1 kV AC network was converted to enable also LVDC operation. As the 1 kV AC and the LVDC applications in rural networks are quite similar, this was the most feasible way to implement the test site. The basic topology of the realised test setup is presented in Fig. 2. The main structure of the system follows the basic concept of public LVDC distribution system [5]. The setup comprises of a 100 kVA rectifying substation, a 1.7 km long underground cabled bipolar ±750 V DC network and, at the moment, three CEIs which supply three-phase 400 VAC voltage for end-users. The system is supplied with two-tier transformer directly from the 20 kV medium voltage network. In case of faults in DC distribution, the system could be quickly returned to normal AC-fed operation.

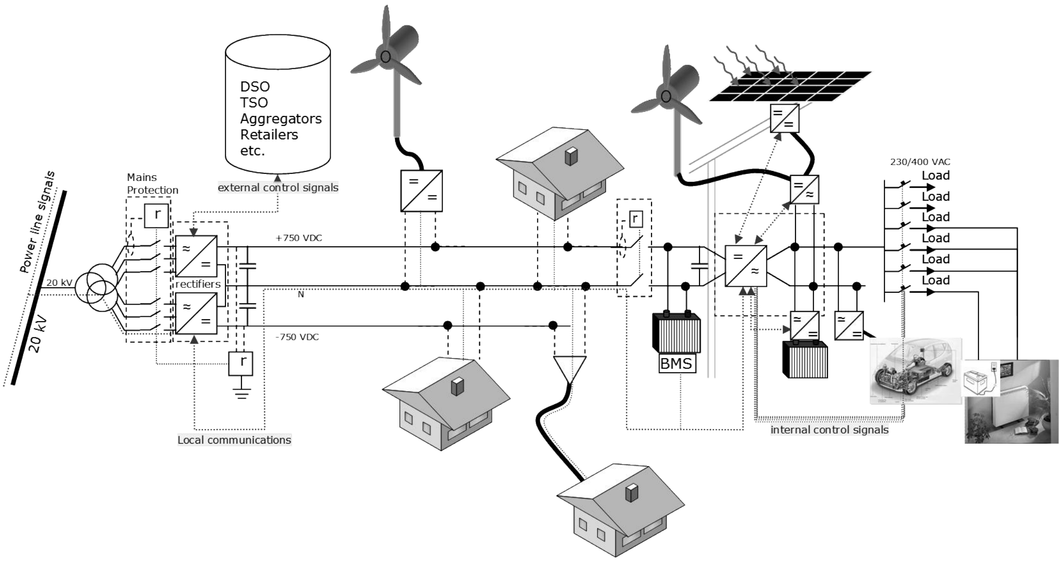

Fig. 1. Example of an active LVDC electricity distribution system with DG and energy storages.

The earthing of the LVDC network depends on the CEI structure. The non-isolated CEI is simpler, but the galvanic connection to the 1.5 kV DC network requires more complicated protection [6]. Without galvanic isolating CEI the whole LVDC system, including the customer-end installations, have to be realised as a terrain isolated unearthed system (IT). Using earthed (TN) systems is not possible without galvanic isolating CEI. Furthermore, realising the DC network as TN system results in dangerous contact voltages especially when the resistance of the earth is high (i.e. in Finland) [7]. Though the IT LVDC network enables both non-isolated and isolated CEI structures, TN network by the customer defines the use of IT DC network.

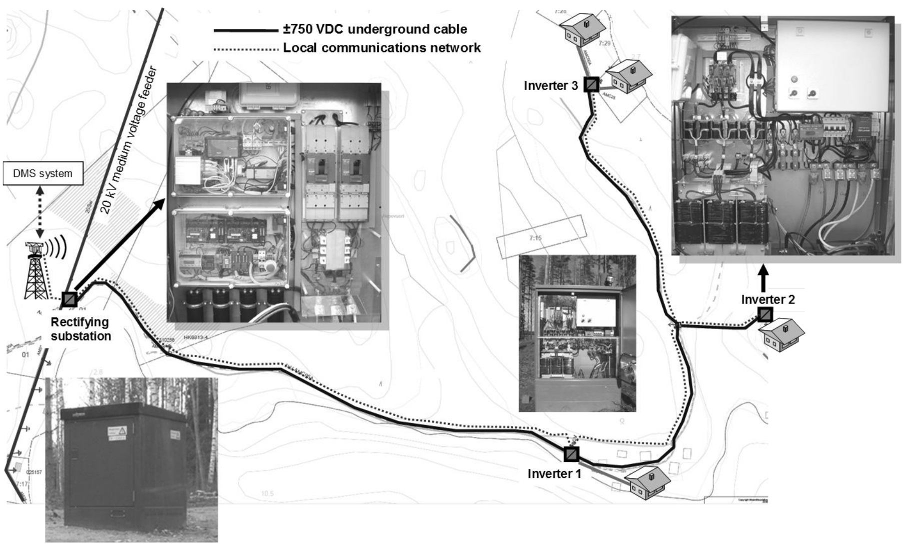

Fig. 2. The real-network research platform located on the map.

The most important design criteria were to enable the realisation of the platform by using commercially available network components as much as possible. It was also essential to ensure that no deterioration in the electric safety is allowed when compared to the existing AC installations. Again, no changes in the customer-end installations were wanted and all CEIs are implemented using galvanic isolation. The installations are designed according to the national low voltage standard series SFS 6000 [8] based on HD 60364, IEC 60364, IEC 60664. The EN 50160 standard [9] was used as a basis for the voltage quality requirements. The protection devices in main power circuit are shown in Fig. 3.

a)
b)

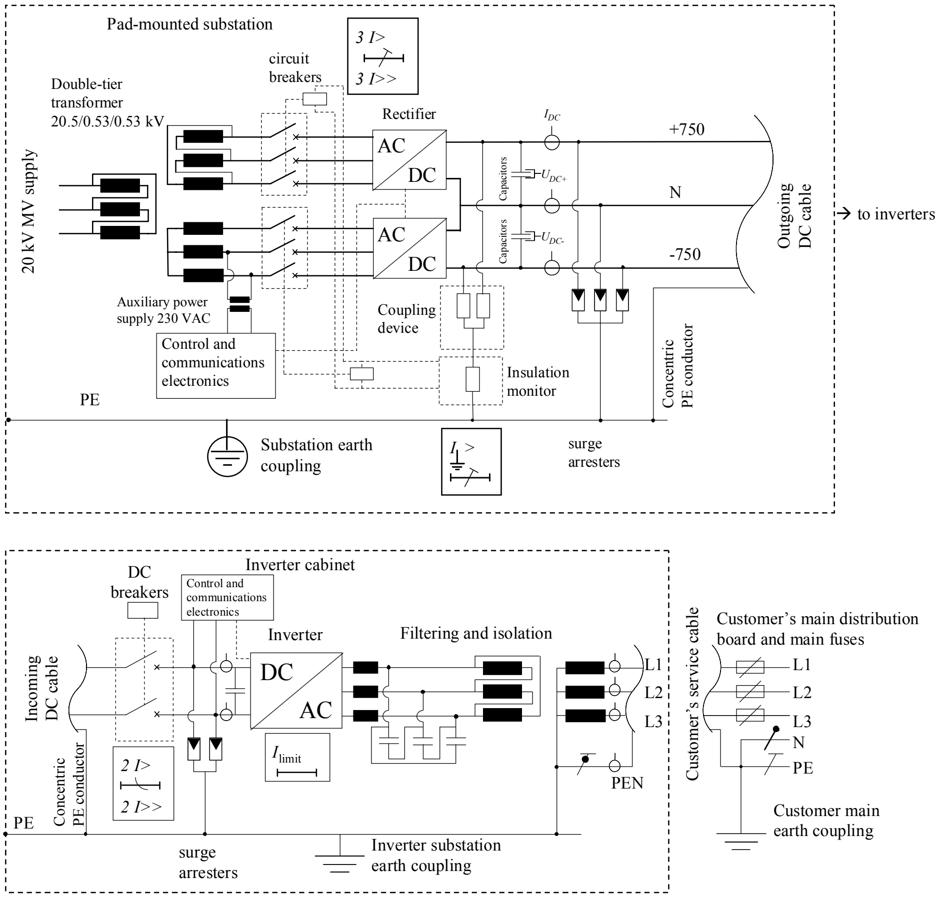

Fig. 3. Main power circuits and protection devices at a) the rectifier and b) the CEI side of the system. There are three similar CEIs in the setup.

INSPECTION ACCORDING TO SFS 6000-6

SFS 6000-6 [8] is based on standard CENELEC HD 60364-6:2006 which divides the commissioning inspection into overall inspections and electrical testing. The inspection of the AC network in Finland has to be done according to the instructions in the standard SFS 6000-6. However, the LVDC distribution network differs from the AC network and therefore, the instructions in the standard might be inadequate or unsuitable. The commission inspections performed in the real-network research platform are described in this paper. The commission inspections were based on the procedure described in the SFS 6000-6 standard, but also several other inspections and tests were performed. The need of these additional or dissident inspections is discussed. The inspections are done only for the new or altered parts of the system. Therefore, the inspection focuses in the DC network and the CEI inspection. No inspections were performed on the customer-end installations being kept intact.

The basic inspection procedure is the same for the LVDC system and low voltage AC system. The system is checked to ensure following requirements

- equipment fulfil safety requirements (1)
- equipment are selected and installed according to requirements in SFS 6000 and by the instructions of the manufacturer (2)
- equipment are not visually damaged such as it might pose a security risk (3)

In real-network research platform, (1) and (2) are problematic because there are components in the network that are either manufactured specially for this *research* application or they are not rated for this type of use. Thus far it is impossible to implement an LVDC distribution using only components rated for LVDC use, because they are not commercially available. Therefore, the non-rated components are selected based on the best understanding of their applicability.

Selection and Settings of Protection and Monitoring Devices

The DC network is protected with similar moulded-case circuit breakers which are currently in use in 1 kV AC network. Voltage on the transformer secondary side being 0.53 kV, 1 kV device is suitable. Because the maximum current of the rectifier thyristor modules is 137 A, the overcurrent trip limit is set to 100 A.

Because the earthing arrangement of the DC network is IT, insulation monitoring (IM) device has to be used. The selected IM device itself is not applicable to DC voltage this high, but the manufacturer is providing a coupling device which expands the voltage rating and enables the use. The IM device controls moulded-case circuit-breakers, also used in short-circuit protection, to disconnect the supply in the case of an earth fault. The device has two resistance settings, alarm and trip. Because the standardisation requires at least 1 MΩ earth resistance, device settings are 4 MΩ and 2 MΩ, respectively. 2 MΩ setting was selected because the IM device manufacturer warrants trip operation if $R_e < 0.5R_{trip}$, where R_e is measured earth resistance and R_{trip} is trip resistance setting.

The CEIs are protected with DC circuit breaker designed for photovoltaic applications. The maximum rated voltage of the used breaker type is 750 VDC and therefore, it is suitable for this setup. With 16 kVA CEI nominal power, circuit breaker with 25 A current rating and B-series tripping characteristics was selected. This means that the high-speed trip (<5 s) is assured when the DC current rises over 125 A and thermal tripping with DC current reaching 36 A for a longer period.

During the sensory inspections, the existence of correct protection devices and their setting values are checked.

Conductor Labelling

Conductor and device labelling has to be realised such that error possibility can be minimised and same conductor colours have to be used in every part of the network. The standard defines blue as mid-point (M) conductor colour in IT DC network. In the setup, conductor labelling is realised differently, because the existing cables are 3xAl+Cu concentric cables without blue conductor. Therefore, all DC conductors are considered as line conductors and the same color order of conductors in bus bar connections can be used in the LVDC as is used in AC system. Again, conductor colours in the setup are brown (L1/L-), black (L2/M), and grey (L3/L+). Concentric conductor is earthed in both AC and DC supply. The existence of labelling and correctness of connections are checked in the sensory inspections against the documentation.

TESTING ACCORDING TO SFS 6000-6

The standard defines the testing procedure for LV networks. Testing methods prescribed are reference methods which enable the use of other available methods, but their properties and safety level should be at least equal. In LVDC network, required tests are discussed in the measuring order proposed by the standard.

Continuity of PE and Mid-Point Conductors of the DC Network

The concentric PE conductor connects together the earth electrodes of rectifying substation and CEI cabinets. Conductor is used for equipotential bonding in whole installation, and depending from the earth connections, decreases the rise of touch voltages and earth potential during faults. Furthermore, the arrangement reduces the EM radiation caused by CEI. From the EMC perspective, connecting the conductor to the earth electrodes in both ends is not necessary. However, connecting separate earth electrodes together can be used for reaching earth resistances resulting in allowable touch voltage levels at CEI, distribution cabinets or at rectifier substation. The connection of all the earth electrodes together is recommendable in all cases as it reduces contact voltages in the whole system, and for instance, reduces the risk of equipment failures due to induced overvoltages, Therefore, the connection and continuity testing of the PE conductor is recommended. In the research platform, the PE conductor of the DC cables is used to connect together the earth electrodes of the rectifier, distribution cabinets and the CEIs. The continuity was measured.

Discontinuity or bad connections of mid-point (M) conductor could result in dangerous rise of voltages in DC network and improper system operation. Because there are capacitors connected between L-, M, and L+, the capacitor voltage could reach 1500 V depending on the resistances in the DC circuit. This overvoltage could cause capacitor and CEI failures. Therefore, the continuity test of the M conductor is necessary in every situation and it was performed according to the standard.

Isolation Resistances of DC Network and CEI Isolation Transformers

The standard defines isolation resistance tests for both IT network and electrically isolated circuits. The isolation of the DC network was measured according to the standard using given test voltages and isolation resistance values. These values were compared with values of the DC network IM device. As a result, the operation of the insulation monitoring device was also verified. At the CEI side, the isolation resistances of the isolation transformers were measured according to the standard using given test voltages and resistance values. Isolation between the DC and customer-end networks is required and isolation failure causes earth fault through customer-end load impedance when the CEI is operating. In this case, the IM device disconnects the supply. Therefore, hazardous voltage by the customer is possible only in double fault situation.

Automatic disconnection of supply in customer-end network

The standard prevents the use of power electronics as a short-circuit protection, because a protection device has to include a contact gap and semiconductor switch is not allowed to disconnect circuit. When no changes are made in the customer-end networks, the short-circuit protection is based on existing devices. Therefore, the CEIs are designed to supply enough short-circuit current. The standard recommendation for the short-circuit current is 250 A_{rms} but it has to be noted that this is only a recommendation trying on aiming on ensuring certain voltage quality in traditional AC installations. From typical household network protection point of view, requirements for automatic disconnection of supply could be fulfilled with lower short-circuit current. CEI short-circuit tests revealed that the saturation of the output filter causes the IGBT current to notably exceed the maximum allowed value and therefore, the short-circuit current is limited to 200 A_{rms} to prevent IGBT failures. In Fig. 4, the effect of the saturation is shown. Transformer primary current i_1 (top) and DC current i_{dc} (bottom) reach the maximum current of the IGBT module (600 A). Still, the most challenging protection device in the customer-end network is gG25 fuse and according to manufacturer gG curves, it will fuse in required 0.4 s time with 200 A_{rms} current, which measured short-circuit current i_2 (middle) also proves.

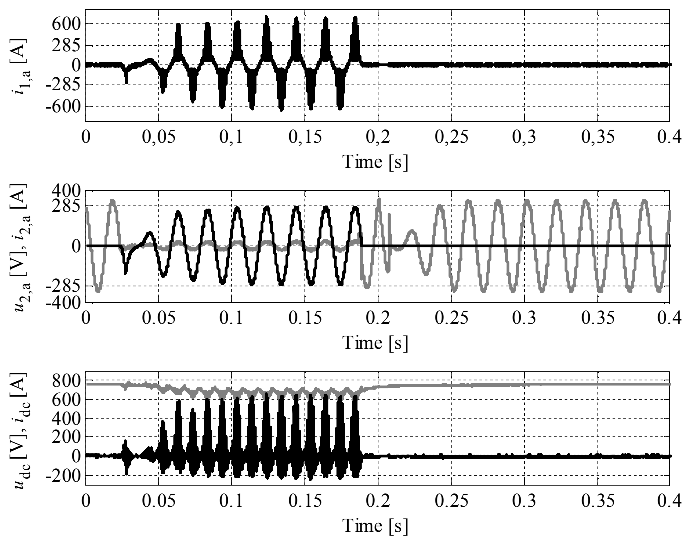

Fig. 4. Measured short-circuit response using a 285 Apeak (200 Arms) current reference.

Though the CEIs were tested in the laboratory, short-circuit tests were carried out also at the field at every CEI, because the short-circuit operation is very important electrical safety matter. Using C20 circuit breaker, a single-phase short-circuit was carried out individually in all three phases and the current was measured using Yokogawa PZ4000 power analyser and

Fluke i1000s current probe. It was ensured from the results that short-circuit current reaches the preset current value and trip time was acceptable. In Fig. 5, short-circuit currents $i_{2,a}$, $i_{2,b}$, and $i_{2,c}$ and phase voltages $u_{2,a}$, $u_{2,b}$, and $u_{2,c}$ in single-phase fault are shown. It can be seen that short-circuit currents reach the preset current value and trip times are acceptable.

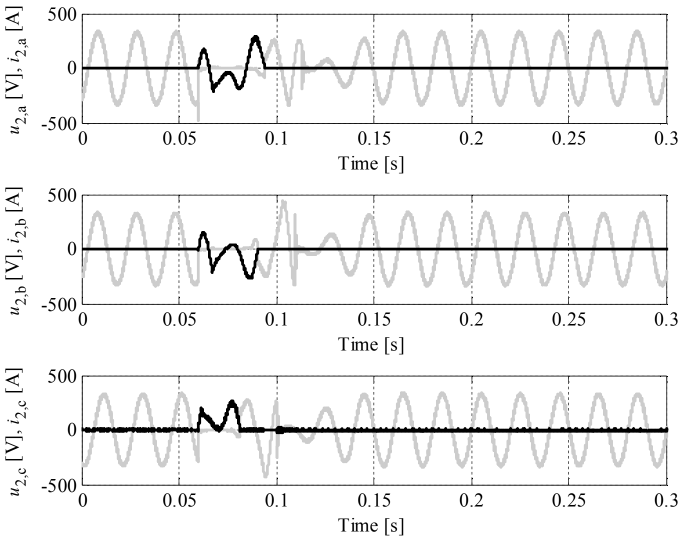

Fig. 5. Short-circuit currents (black) and phase voltages (grey) during single-phase fault in phases L1 (top), L2 (middle), and L3 (bottom). Protection device used was C20 circuit breaker.

In order to fully utilise the benefits of the LVDC distribution system in the future, the standardisation of distribution systems should also consider the aspects of DC distribution. Feeding high-amplitude short-circuit current has some obvious drawbacks and makes the converter design and control more challenging. With alternative methods, reducing the short-circuit current without threatening the electrical safety of the customer is possible. These methods are discussed in more detail in [10].

Automatic disconnection of supply in DC network

Verifying the operation of automatic disconnection of supply in AC networks is performed by measuring the short-circuit impedance of the network. In DC network, the impedance cannot be measured because the rectifier is located between the supplying transformer and the network. Because the short-circuit impedance of the transformer seen from the DC network depends on the commutation current of the rectifier, the impedance cannot be specified by adding together cable and transformer impedances. Therefore, the automatic disconnection of supply in specified time was verified with measurements by shorting the network in the electrically furthest location.

In addition to the short-circuit protection, the operation of the IM device has to be tested. Though the standard allows the DC network use in case of earth fault for 2 hours with alarming protection device, the IM device will disconnect the network in 5 seconds. The operation of the insulation monitoring device was tested by earthing one conductor at a time in de-energised network. With every conductor, it was observed that the IM device operated in specified time.

DC connections and polarity

The wrong conductor order of the DC cable could result in electrical safety hazard or equipment failure. Because the DC network is realised using bipolar connection with ±750 V voltage levels, the maximum voltage in the DC network is 1500 V. The CEIs are connected to either upper or lower voltage level and their nominal DC input voltage is 750 V. Therefore, the wrong connection of the cable could result in CEI input voltages double the nominal value. This result in DC capacitor failure and possible other faults if the overvoltage is applied long enough. The CEI will not start until the voltage is in rated voltage range and therefore, IGBT overvoltage failures would not occur.

It is also possible to connect the cable such that the polarity is reversed either in both voltage levels or only in one. This causes short circuit at every CEI because IGBT module includes a diode bridge connected in reverse direction. The DC voltage over the shorting circuit depends on the conductor order and it is 750 V or 1500 V. With 750 V, the short circuit causes DC circuit breaker trip because the diode bridge can withstand such overcurrent. Short circuit with 1500 V voltage is more dangerous situation. Because the rated voltage of the DC circuit breaker is 750 VDC, the proper operation could not be guaranteed. If the circuit breaker fails, at least the IGBT module will break down. The correct conductor order was inspected using conductor colour codes. In addition to this, the all CEI side circuit breakers were opened and DC voltage levels were measured at every CEI in energised DC network.

Voltage quality and direction of rotation

Self-manufactured CEIs are designed to fulfil voltage quality requirements by the EN 50160 [9]. Because the customer-end network is supplied with CEI, the voltage quality is maintained locally and therefore it has to be included in the inspection procedure. Though the CEI has been tested in the laboratory, the properties of the output voltage were verified. Because the CEI enables constant voltage quality control, the aim was to keep voltage properties within tighter limits than the standard requires. Therefore, following voltage requirements were used in the measurements

- Frequency: 50 Hz ± 0.1 %
- Voltage level: 230 V ± 1 %
- Harmonic distortion (THD): < 3 %

Frequency and voltage levels were measured using the power analyser and Fluke multimeter. In Fig. 6, phase voltages of one CEI are shown. The deviation of the frequency was wanted to keep as small as possible, because the CEI can keep the frequency constant in every load condition. However, it is possible to alter the frequency if customer-end load control is wanted to use in the future. The direction of rotation of the customer-end network is measured using methods presented in the standard. If the direction is incorrect, it can be corrected by re-programming the CEI.

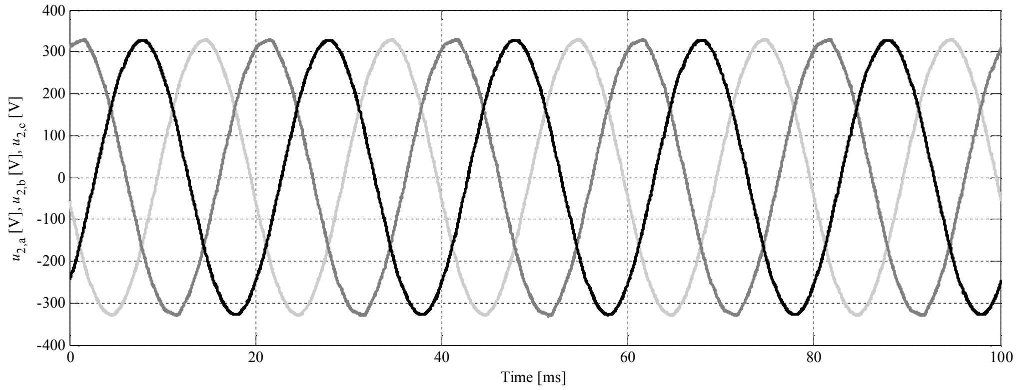

Fig. 6. Phase voltages of one CEI.

Functional tests

The standard requires that functional tests have to be performed before initial start-up. In addition to normal functional tests, such as switches and indicators, further tests were performed. Because the rectifier and the CEIs can be remotely controlled and monitored using web application, all control functions were tested and it was observed that all available measurement values were available. Also, the application logon security and switchover between primary and backup network connections were tested. The DC network can be disconnected using rectifier moulded-case circuit breakers in case of emergency by pressing emergency stop button by the rectifier or on the web application. Both methods were tested.

The CEI also includes additional intelligent protection functions. These functions are tested in the laboratory before implementing the CEI in real network and they were not included in test procedure. Protection functions are

- DC under- and overvoltage
- customer-end under- and overvoltage (RMS and peak values)
- limited number of sequential shutdown-start-ups
- IGBT and cabinet temperatures
- control electronic supply under- and overvoltage
- frequency deviation
- maximum short circuit duration

Common-mode Interference and EM Radiation

The power electronics could cause common-mode Interference and EM radiation. The common-mode radiation is decreased by using the isolation transformer between the customers and the DC network. Isolation transformer being widely used method for decreasing conducted interference, no tests were performed in commissioning inspection concerning common-mode interference. EM radiation is decreased by earthing the concentric conductor of the DC cable. However, these are very important research issues and measurements concerning interference and radiation will be performed in future.

CONCLUSIONS

In this paper, commissioning inspection in *research* platform in public network is presented. The scope of the paper is not provide suitable inspection protocol for LVDC network but discuss mandatory tests which are needed when such setup is implemented in public network. The challenge of the commissioning inspection is the lack of official inspection procedure and commercially manufactured components. Therefore, performed tests were selected to ensure person safety, equipment safety, and proper functioning of the system.

When system components are commercially manufactured, the manufacturer performs some of the tests and certifies that the component fulfils given specifications. Tests performed by the manufacturer are rectifier and CEI short-circuit current capability and operation in short circuit, CEI voltage quality, and intelligent CEI protection functions discussed above. In addition to these functional requirements, components have to

- fulfil electric safety regulations
- fulfil input voltage requirements
- fulfil output voltage quality requirements
- be compatible with other network components
- withstand installation to specified conditions

Today, the challenge in component development is the insufficient data of component requirements for the LVDC network. There are no type testing standards available and manufacturers are unable to reliably certify the components. Realisations of the actual network setups enable verification and development of system design principles, equipment structures and installation techniques. The global interest towards LVDC distribution has increased during past years. An indication of this is the foundation of the IEC LVDC strategy group (SG 4) in year 2009, the objective of which is to guide the development of LVDC standardisation. The IEC SG 4 has recommended that the LVDC distribution standardisation should be done by application areas based on market needs and availability of practical experiences. Therefore, further studies are required to gain more experience concerning the LVDC distribution.

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