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Operating experience and ways to improve reliability of Vyborg back-to-back HVDC link (in connection with the 35th anniversary of the commissioning of the first converter unit)

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SUMMARY

The Vyborg back-to-back HVDC link, providing asynchronous connection between power networks of Russia and Finland, is in operation since 1981. Vyborg converter substation includes four identical High Voltage Converter Units (HVCUs) rated at 355 MW each.

For many years JSC "NIIPT" have been working on analyzing the outages of the equipment of Vyborg converter station and developing recommendations to improve its operation reliability. This paper summarizes the results of the development and modernization of the Vyborg converter station equipment aimed at increasing its functionality and reliability over the last 10 years.

The commissioning of new equipment at the Vyborg substation for the purpose of reconstruction and expansion was completed in 2003. The integrated control, protection and automation system was successfully tested and put into operation at the four HVCUs 1-4 in 2003-2004. Operational experience of the control and protection systems was satisfactory; in 2007-2008 minor corrections were made. For example, the vendor proposed to make a desensitization of the backup circuit of commutation failure protection (CFP) to reduce the probability of false protection triggering when the rectifier operates with small firing angles. After implementation of this improvement, there was no false triggering of CFP at all four HVCUs. Some improvements of the C&P system were made to reduce overvoltage when HVCU-4 was switched over to a dedicated overhead 400 kV line. Software for implementing power reversal was created and system tests of HVCU-4 reverse mode were completed in 2010.

In 2007 there were three cases of voltage collapse at 400 and 330 kV buses. One failure resulted in 850 MW power loss, being the severest accident in that year. In two other cases the development of accidents was prevented due to HVDC link power decrease. In this connection, the regimes of Russia-Finland transmission were studied to determine the sufficiency of reactive power sources and to develop measures to prevent voltage collapse.

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Studies were carried out to determine the allowable transmission power while reducing the short-circuit power at 400 kV buses. Power controller was adjusted to reduce the probability of voltage collapse.

Appropriate adjustments were made to the power control system to implement the frequency load shedding algorithm in accordance with the demand of System Operator.

The power control system was also adjusted in connection with the introduction of STATCOM equipment with a capacity of 50 Mvar. STATCOM was commissioned in December 2011.

To improve the reliability of the HVDC link at energizing of unloaded converter transformers some recommendations were developed.

The main equipment of the Vyborg converter station has worked longer than the normal operating period and is overaged. Nevertheless, the reliability of the equipment remains relatively high. According to the outage statistics for 2007-2016, the HVCU’s average forced outage rate is 4.9 per year. The main cause of the HVCU’s forced outages is leakage of cooling liquid in the valves cooling system, which needs improvement.

Reconstruction of Vyborg HVDC back-to-back link is scheduled for the near future. Thyristor valves and reactive power compensation equipment are scheduled for replacement. Improving the protection of filter capacitor banks is planned. It is necessary to develop and implement a protection system including diagnostics of capacitors, which will detect internal failures, such as blown fuses. It is also planned to carry out a comprehensive reconstruction of the cooling system.

KEYWORDS

Vyborg HVDC back-to-back link, control and protection system, power controller, algorithms, voltage collapse, reverse, field system test, frequency load shedding algorithm, reliability, forced outage, reconstruction

1. INTRODUCTION

December 2016 marks the 35th anniversary of commissioning of the first converter unit of Vyborg converter station. Vyborg back-to-back HVDC link is part of reverse cross-border electrical power transmission Russia - Finland.

Vyborg back-to-back HVDC link includes four High Voltage Converter Units (HVCUs) rated at 350 MW each and a switch unit with AT-3 330/400 kV autotransformer, which enables dedication of one of the power units of the North-West CHPP to parallel synchronous operation with the power system of Finland (Figure 1).

Three of the four HVCUs were commissioned in the eighties, the fourth unit was put into operation in 2000 [1].

Development and operating experience of Vyborg back-to-back HVDC link equipment is of key importance both for the development of HVDC technology in the Russian Federation and for planning refurbishment of HVDC back-to-back.

Technical solutions implemented in the high-voltage thyristor valve (HVTV) of Vyborg converter station meet the basic world tendencies: modular design, light pulse control system, auxiliary power supply from high valve potential, cooling with de-ionized water, and others.

The valves had been put into operation at first stage with thyristors T-630 connected 3 in parallel. Parallel connection of thyristors was applied due to the fact that I_{TAV} of one thyristor was less than the unit's rated steady-state current. Six modules formed one valve block, which represented a phase of a 6-pulse bridge. One control board was provided for each HVTV block. Completely new thyristor modules had been developed in the mid-90s when new thyristors of type T273-1250 became available. A module consists of 4 series-connected thyristors; a valve contains 16 modules. One control board is used for the entire valve bridge [2]. After the HVTV was refurbished in 1999, the maximum permissible level of the direct current of the HVCU was increased from 2100 to 2400 A.

Since 2000, cross-border electrical power transmission Russia – Finland was refurbished significantly with the aim of increasing capacity. The fourth HVCU was built and put into operation, i.e. the installed capacity of converters was raised up to 1400 MW.

Two more 330 kV overhead lines (OHL) were put into operation, the total number of 330 kV OHL was brought to four, the power transfer capability of each line is 600 MW. A third 400 kV OHL was put into operation, so the Vyborg substation was connected to the Ylikkälä substation through two 400 kV overhead lines and to the Kymi substation through one line, power transfer capability of 1000 MW each.

The capacity of the filter-compensating units (FCU) has been significantly increased: a third capacitor bank on 400 kV buses has been put into operation and additional capacitor banks CB-35 kV were connected to the tertiary windings of the converter transformers of HVCU-3 and HVCU-4.

A unit of the North West Power Plant was provided for the synchronous connection to the Finnish power system via a 400/330 kV autotransformer installed at Vyborg converter station and two OHLs of 330 kV and 400 kV. It is possible to switch over HVCU-4 from the 400 kV buses to the 400 kV overhead line and if necessary also to the 330 kV overhead line for back up purpose.

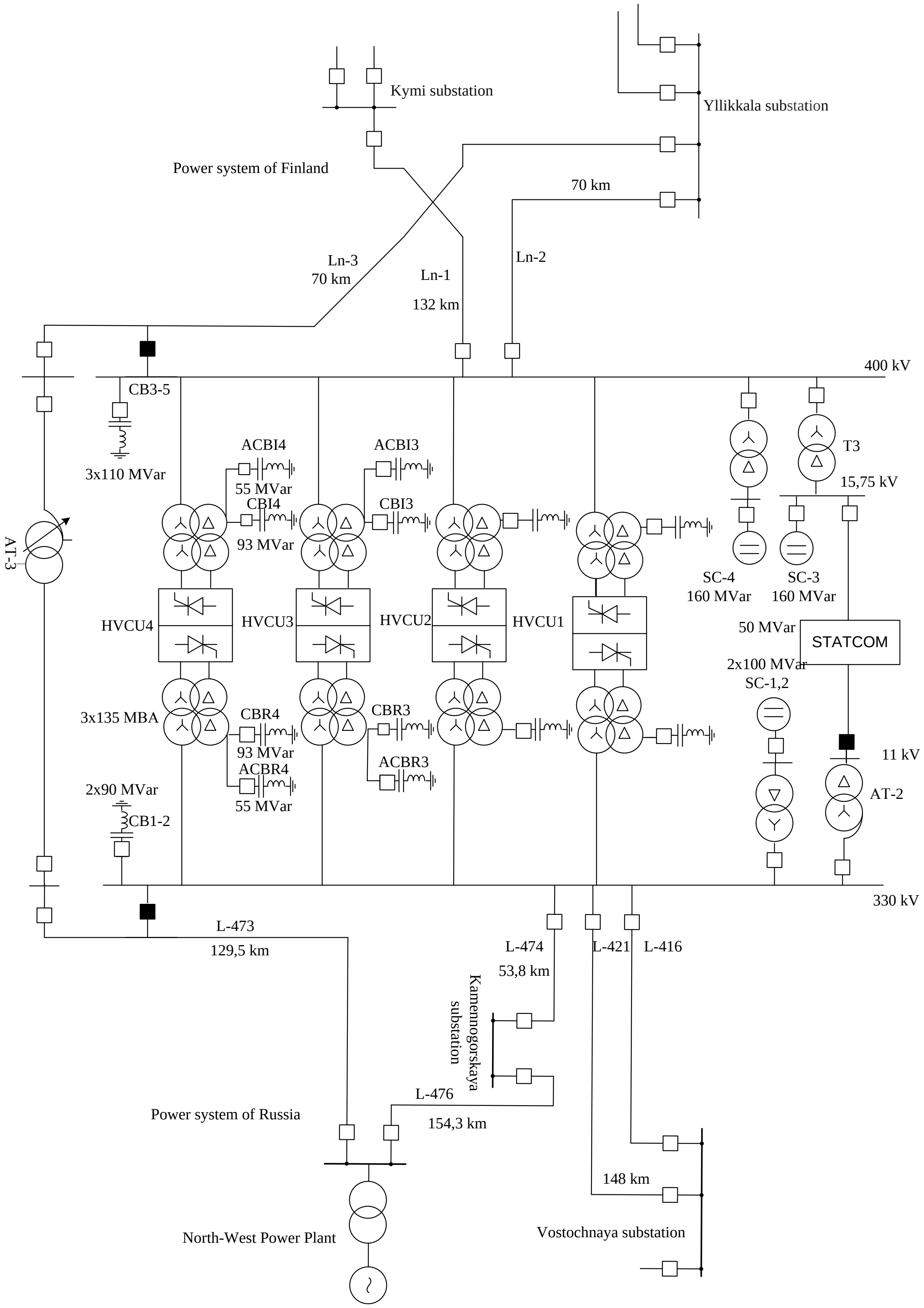

Figure 1 – Circuit diagram of Russia-Finland cross-border connection: HVCU – High Voltage Converter Unit, CBR(I) – rectifier (invertor) capacitor bank, ACBR(I) – additional rectifier (invertor) capacitor bank, CB – capacitor bank, SC – synchronous compensator

First production prototype of the integrated control, protection and automation system was successfully tested and put into operation on the new fourth HVCU-4 in August 2003 [3]. The control system is implemented on the basis of processor CPC 102.01 with a clock rate of 200 MHz. The control and protection system has triple modular redundancy in which three parallel operating sets perform a process and result is processed by a majority-voting system to produce a single output. Old C&P systems were replaced at the remaining HVCU-1,2,3 step by step in 2004. During the commissioning of the C&P system for the next HVCU, software was upgraded to take into account the operating experience of already commissioned C&P systems. An exact copy of control and protection system of HVCU (replica) is installed at Vyborg converter station. The replica is connected to a physical simulator and intended for testing and validation of the upgraded algorithms and hardware before field implementation.

The paper summarizes the results of the development and modernization of the Vyborg converter station equipment aimed at increasing its functionality and reliability over the last 10 years.

2. CORRECTIONS OF THE CONTROL AND PROTECTION SYSTEM ALGORITHMS

The commissioning of new equipment at the Vyborg substation for the purpose of reconstruction and expansion was basically completed in 2003. Operational experience of the control and protection system was satisfactory; its functional algorithms and setpoints were tested and fine-tuned; in 2007-2008 minor corrections were made.

In 2003-2008, false trips of commutation failure protection (CFP) were recorded when the rectifier operated with little firing angles.

To ensure a secure firing of the thyristor valves and to exclude the control impulse generation in the negative voltage zone, there is an algorithm ensuring the fulfillment of the following condition. Changing the sequence of the rectifier control impulses (i.e. the appearance of the next control impulse) is allowed under condition that commutation voltage value for the commutated valve is not less than 8-9% of the nominal voltage amplitude.

Minimum voltage is monitored by hardware with special triggers, which cannot provide a strictly simultaneous voltage level detection. Therefore, the next impulse in different sets of C&P system can be generated non-simultaneously. If a control impulse is generated and there is no valve current, conditions for triggering protection are created in the set of C&P where the control impulse appears earlier. The fault detector of the reserve channel of commutation failure protection triggered when the valve currents and control pulses did not match during three cycles of the C&P system. The vendor proposed to make a desensitization of the backup circuit of CFP – to increase the protection operation delay up to four cycles. After implementation of this improvement at all four HVCUs, the probability of false CFP operations was diminished.

In 2007, studies of the overvoltage occurring when HVCU-4 switched over to a dedicated 400 kV overhead line were carried out. Based on these studies, the following recommendations were given:

1. To avoid excessive overvoltage protection trips on the inverter side when switching on the capacitor bank (CBI) or in case of a short circuit in the 330 kV AC system, the protection setpoint should be increased from 1.5 to 2.0 p.u. (per unit value referred to the amplitude of the nominal phase voltage).

2. To reduce overvoltage on the tertiary winding of the inverter transformer when the HVCU trips off, it is necessary to reduce the current ramping rate during the tripping process.

After the corrections of the control system mentioned above were implemented, HVCU-4 is able to be switched over to a dedicated 400 kV overhead line Ln1 directly, without preliminary connection of the HVCU-4 and the Ln1 to the 400 kV bus.

3. MEASURES FOR PREVENTING VOLTAGE COLLAPSE

For the first time voltage avalanches at the Vyborg substation were recorded in 2003. These cases began to be recorded after the expansion of the substation and increase in the transmitted base power, as well as with a decrease of the short-circuit ratio of adjacent 400 kV AC system. Voltage avalanches were recorded when 400 kV lines were tripped off.

Voltage avalanche process, which ended up with the shutdown of three HVCUs, is described below. At the initial stage of process, HVCU-4 with power of 300 MW was connected to dedicated Ln1, HVCU-1-3 with total power of 820 MW were connected to common bus 400 kV and Ln-2,3.

Due to false operation of the automation at the Ylikkälä substation, Ln-3 was tripped, which resulted in reduction of SCR of the Finnish power system. The short-circuit power at the 400 kV AC side decreased to 2315 MVA. The emergency process resulted in a shutdown of three HVCUs, complete de-energization of 400 kV buses, and 850 MW power loss. The initial stage of development of the process is shown in Figure 2. Distortion of voltage waveform in the transient process resulted in subsequent DC current reference and converters power drop. At the same time, the reactive power flow and the power of the synchronous compensators did not change. The further development of the failure was triggered by the power controller, which began to increase DC current reference in order to maintain the active power as it was supposed to do according to its algorithms (Figure 3).

DC current reference ramping up occurred within 5 seconds, but it did not affect the actual power transmitted by Ln-2 due to reduction of voltage on the 400 kV buses. The reactive power consumed from the Finnish power system increased to 316 MVar over 10 seconds, the 400 kV bus voltage dropped from 408 to 335 kV. Despite this fact, the converters continued to operate steadily. Approximately 45 seconds after the Ln-3 tripped, an additional capacitor bank (ACBI-3) was put into operation to maintain the 400 kV bus voltage (this decision was made when the voltage dropped down to 380 kV), which resulted in unstable operation of the HVCU and ~78 Hz current component in DC circuits (Figure 4), and HVCUs 1-3 were tipped off by the protection systems.

Power control system at Vyborg substation has a remote control channel from the Finnish power system which allows for active power reference ramping within ±10% of the current value of power reference at a rate of 30 MW per minute. Power ramping up upon the buyer's request without SCR evaluation can be resulted in voltage collapse and converter trip off. Such voltage avalanche processes were eliminated by the dispatcher manually by disabling the remote power control channel.

Studies were carried out to determine the allowable transmission power while reducing the short-circuit power at 400 kV buses. In these studies, the transmission power limits via Vyborg substation were calculated under various 400 kV network configurations and with different equipment of the Vyborg substation. It is shown that in the most probable operation mode with three HVCUs and one 400 kV line the capacity of 1000 MW can be guaranteed only if the voltage in the Finnish power system is at least 400 kV.

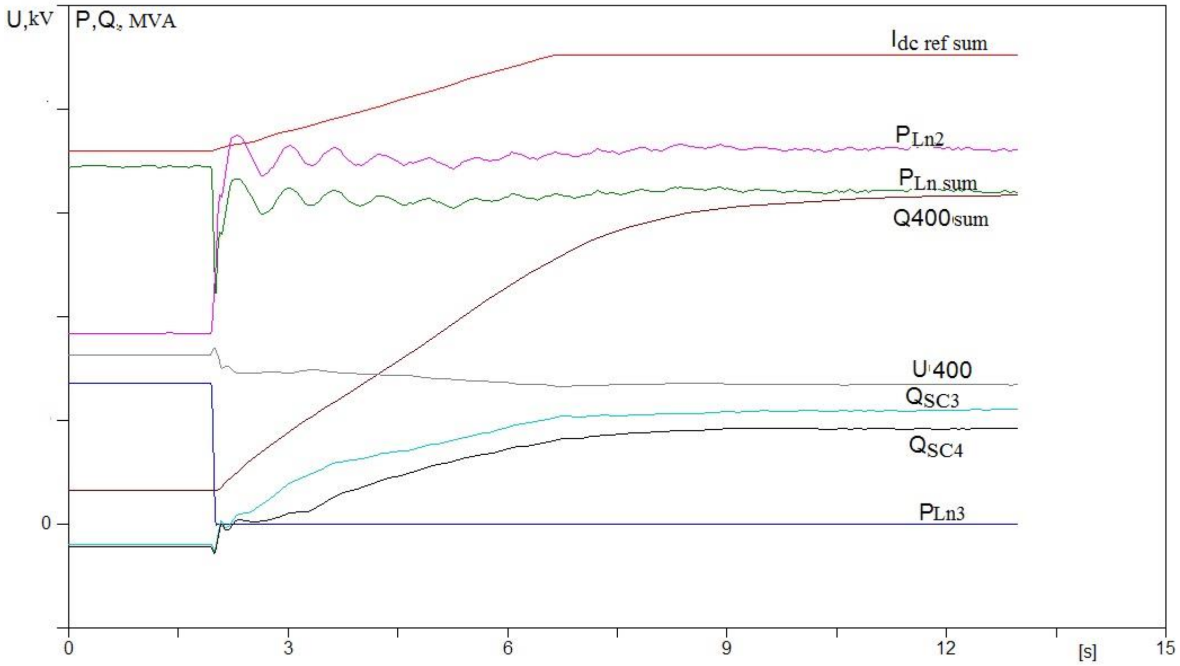

Figure 2 – Initial stage of voltage avalanche process

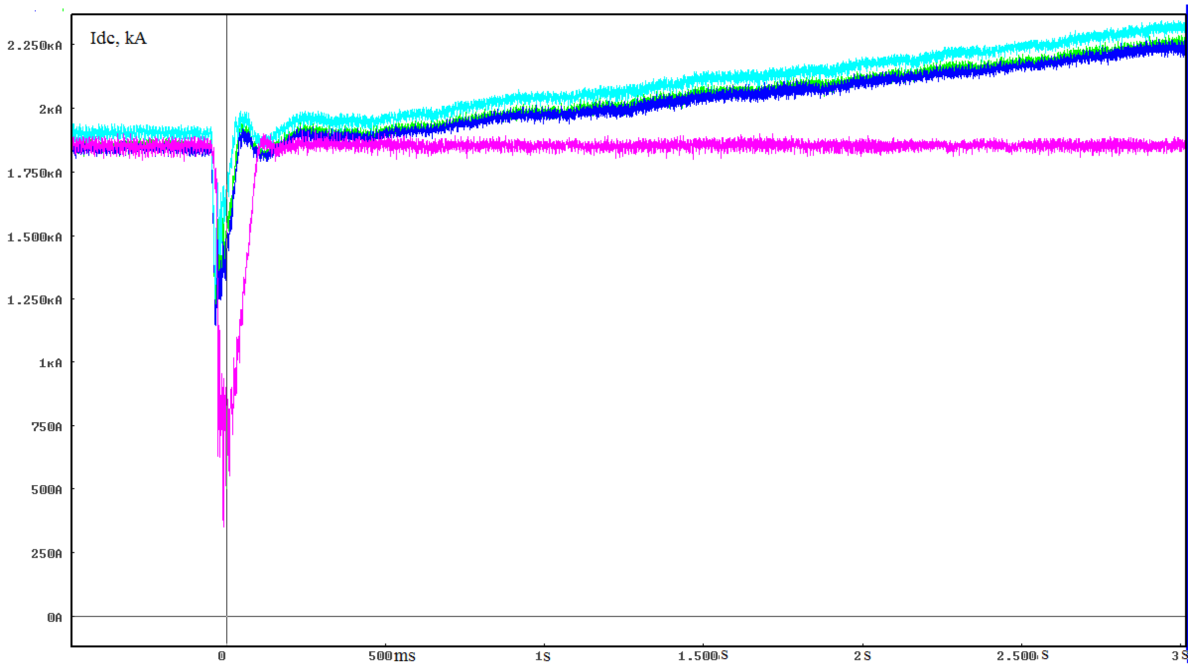

Figure 3 – HVCU 1-4 DC currents

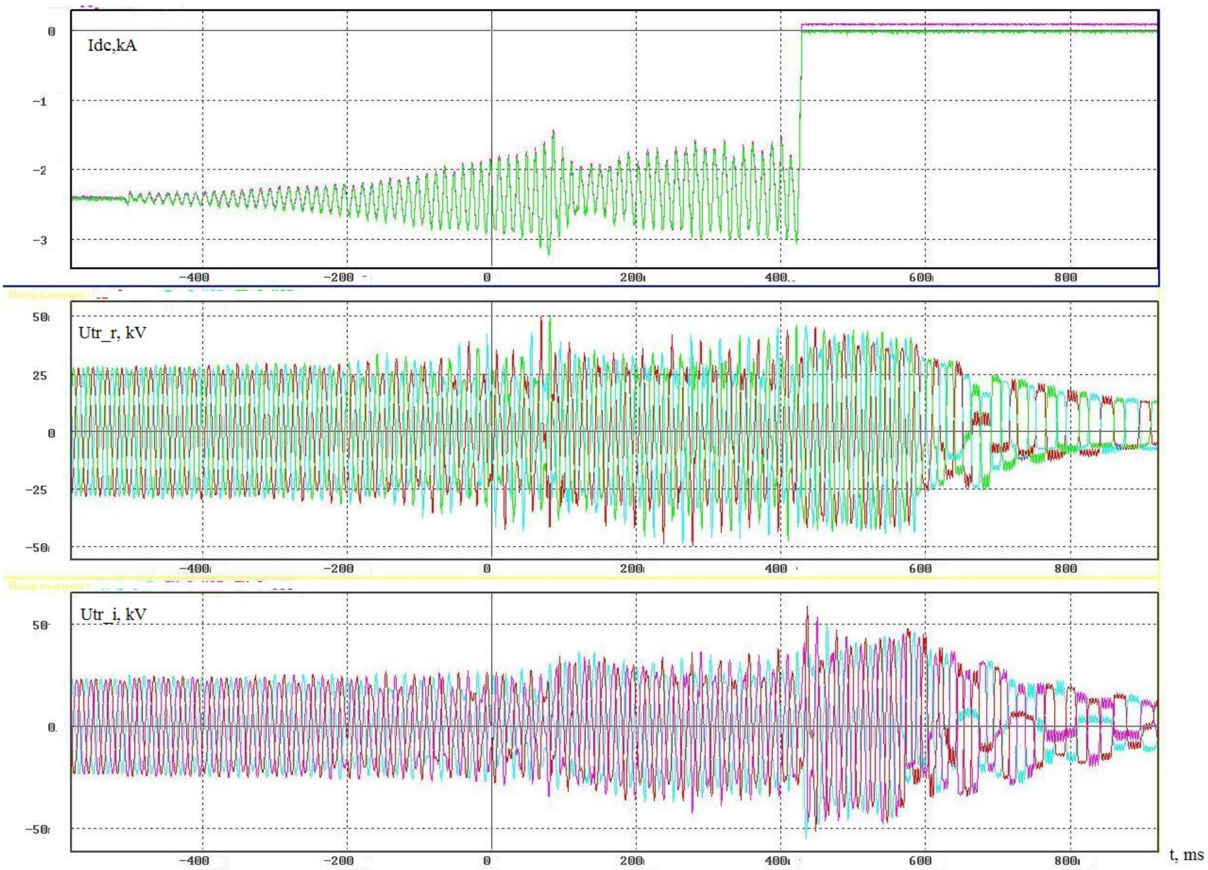

Figure 4 – HVCU-2 tripping off: Idc – direct current HVCU-2, Utr_r, Utr_i – rectifier (inverter) tertiary winding voltage

In 2008, the power controller algorithms were adjusted to reduce the probability of voltage avalanche. The following adjustments were proposed. The sign of voltage decreasing D_{LV} is formed by the algorithm:

$D_{LV} = ((U_{400} < U_{LV400})$ and $(Q_{\Sigma 400} > Q_{MIN400})) \mid (U_{400} < U_{LV400MIN})$,
where U_{400} is 400 kV bus voltage,
U_{LV400} = (340 ... [380]) kV,
$U_{LV400MIN}$ = (340 ... [370] ... 380) kV,
$Q_{\Sigma 400}$ is total reactive power of 400 kV lines,
Q_{MIN400} = (100 ... [150] .. 200) MVar.

If the voltage continues to drop during a specified time delay T_{LV}, active power reference is reduced by a specified value ΔP_{ref}.

4. REVERSE MODE OF HVCU-4

Since 2008, works have been carried out to implement the reverse mode of HVCU-4. Software has been created for the reverse mode (HVCU-R). The main goal of reverse mode implementation at the 400 kV Vyborg station was to create a more competitive market environment in the area of electricity transmission between the countries.

It was assumed that the modernization of the C&P system should be as cheap as possible and with maximum use of the existing C&P capabilities while on the other hand reliability of the new control system shall be at least at par with the presently existing one. Moreover, debugging and commissioning of a new version of C&P-R (reverse) system should take minimum time.

The greatest modification of the C&P-R hardware in comparison with the non-reversible version of the existing controller was made in the processing of the controller's input and output signals. A new version of the CCB2 (cross-connection board for exchange of the majorized signals between three identical C&P-R sets) and the switching board of the currents and voltages logic signals were developed.

The algorithm of tap controller was completely redesigned, settings of commutation failure protection system were changed, overvoltage protection algorithm on the inverter side was also redesigned.

Testing of all C&P-R systems was carried out with a physical simulator: control system; converter protection system; automation system. Special attention was paid to the modified software.

C&P system includes overvoltage protection (OP) on inverter side. In case of overvoltage at the 35 kV transformers connected to 400 kV buses, the protection system trips the converter and transformers. Updating of overvoltage protection algorithms was required for two reasons. First, 330 kV transformers must be also equipped with overvoltage protection. Second, the overvoltage protection revealed some disadvantages; the main problem was that the operating time did not depend on the overvoltage magnitude. Operation was delayed by time t_2 = 20 ms.

With the heaviest failure in terms of overvoltage – sudden disconnection of 400 kV buses from the Finnish power system and all 400 kV lines (so-called "transmission break") – overvoltage protection must trip with a shorter time delay. New overvoltage protection algorithm provides reliable protection operation for any kinds of overvoltage. Overvoltage protection operating time depends on the overvoltage magnitude; this ensures triggering of the OP upon a "transmission break" failure within a few milliseconds. In particular, the protection operating time is 5 ms when the voltage exceeds the setpoint value by 9%.

To prevent OP unnecessary operations at allowable overvoltage level when HVCU switches over to a dedicated 400 kV line, CB-35 kV tripping on, as well as short-circuits in a 330 kV power system, it is necessary to select OP setpoints very accurately.

Oscilloscope charts in Figure 5 show the transient process when the overvoltage protection system is triggered at the 330 kV side with the control system operating for a physical model. Linear voltages are shown from the 330 kV side that are obtained with the physical simulator in reverse mode (400 kV → 330 kV) with rectified current of 1000 A as well as some C&P signals. From the charts it is also possible to see the rising reversible counter of the protection trip delay as the voltage increases above the setpoint from the 330 kV side (spn2) and generation of zsz1 signal to trip the unit from the protections. Overvoltage protection time delay is 49.6 ms.

At the first stage of the field system tests the following scheme was chosen: HVCU-4 operates in reverse mode, HVCU 1-3 transmit electricity to the Finnish power system. Conducting field system tests using this scheme does not require a revision of the intersystem agreement and terms for energy metering, since the total energy flow is transmitted to the Finnish power system. The Finnish power system perceives this test mode as a normal mode with lower transmitted power. A specific feature of this mode is that, despite the relatively small amount of transmitted power in this scheme, the total consumed reactive power is significant. When HVCU-4 transmits 350 MW from Finland to Russia, three HVCUs 1-3 transmit 550 MW from Russia to Finland, consumed reactive power at 330 and 400 kV buses will correspond to the reactive power consumed as if all four HVCUs transmitted electricity from Russia to Finland.

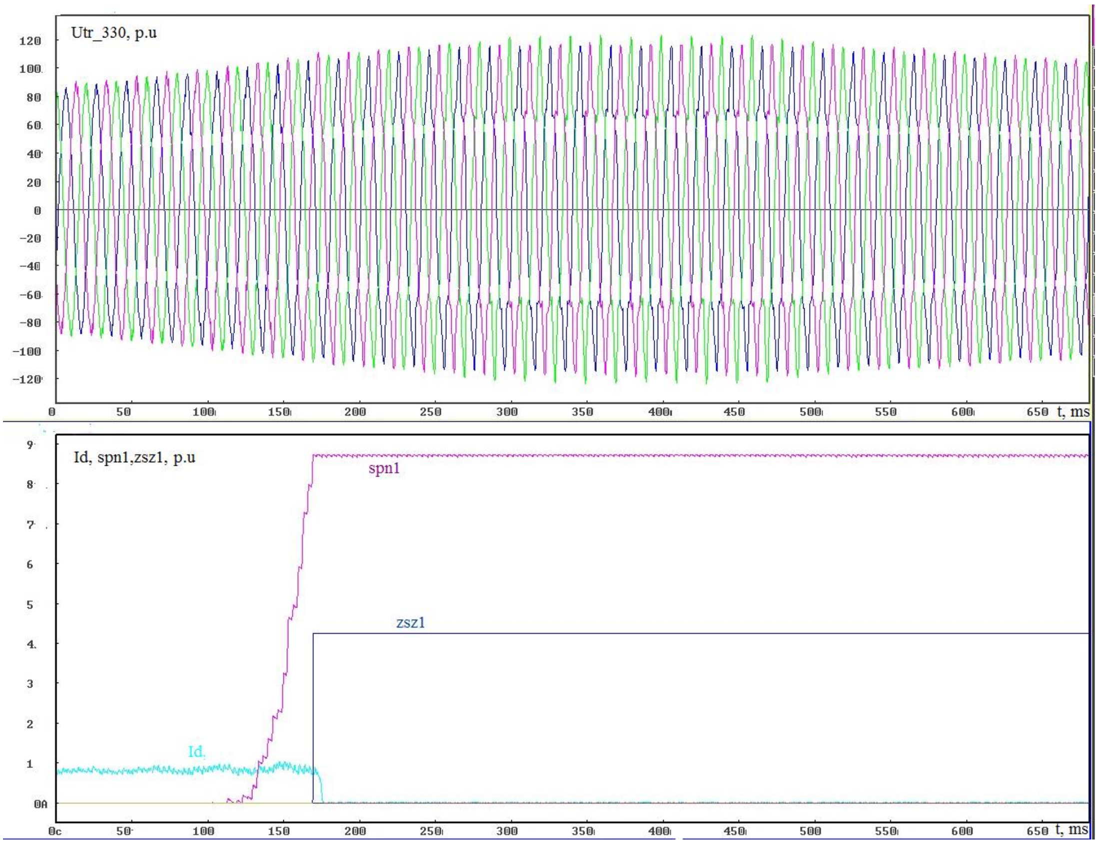

Figure 5 – OP tripping during operation of C&P-R system with physical simulator in reverse mode: Utr_330 – tertiary winding voltage 330kV, Id – DC current, spn2 – output of time delay counter, zsz1 – tripping signal

When the transmitted power of HVCU-4 was up to a value of 260 MW (Figure 6), power fluctuations of 75 Hz were recorded in the DC circuits of all HVCUs. Further power ramp up was stopped. Since the measured power in 400 kV lines was 550 MW, the power controller calculated the reference value of extinction angles of inverters HVCU-1, 2, 3 at the level of 30^0. Actually, the power of four HVCU was 1070 MW and the consumed reactive power corresponded to the load of 1070 MW, since LCC always consume reactive power regardless of whether they operate as rectifier or inverter. When transmitting a power of 1070 MW from Russia to Finland, the extinction angles of the converters must be installed at the level of 18^0. The mismatch of extinction angles and the actual power flow caused the fluctuations of direct current.

In 2010, system tests of HVCU-4 in reverse mode were completed. The tests scheme imitated the operation of HVCU-4 with a weakened Finnish power system. Inverter transformer TI4 was energized from North West Power Plant generators via overhead line L-473 and autotransformer AT3. During system tests the HVCU-4 current was ramped up to maximum value.

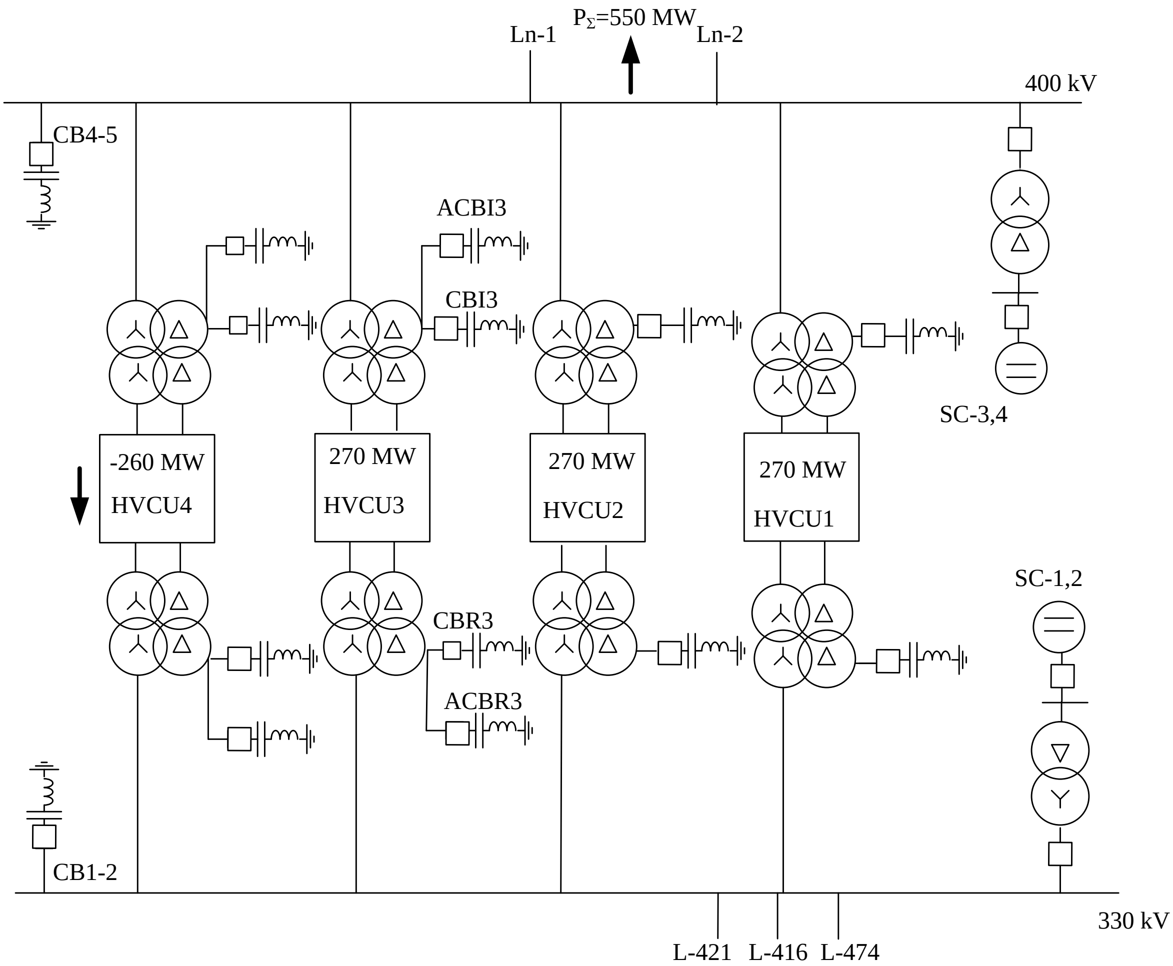

Figure 6 – Operation of HVDC back-to-back with HVCU-4 in reverse mode

5. CORRECTION OF C&P SYSTEM ALGORITHMS FOR IMPLEMENTING AUTOMATIC FREQUENCY LOAD SHEDDING FUNCTION

Appropriate adjustments were made in the power control system to implement the frequency load shedding algorithm in accordance with the demand of System Operator.

To ensure steady operation of the North-West part of the power system of Russia in emergency conditions, it is possible to reduce the power flow through the Vyborg back-to-back with a decrease of AC power system frequency. Depending on the magnitude of the frequency deviation and the duration of the deviation, step-wise drop of transmitted power by a value from 200 to 350 MW is available. Power order change is made upon the command from the AC power system. Active power transmission through the HVDC link can be quickly reduced within 0.04 s after receiving the command.

6. STATCOM COMMISSIONING

Power control system was also adjusted in connection with the introduction of STATCOM equipment with a capacity of 50 Mvar. The STATCOM demonstration project was commissioned in December 2011 [4].

Given the small power of STATCOM (about 4.5% of the total power of compensating devices at 400 kV bus), the main objective of the Vyborg STATCOM demonstration project was the accumulation of operating experience, regarding both reliability of the power equipment and integration with automatic control and reactive power regulating systems. Besides, STATCOM was considered as the basic unit for future FACTS.

The STATCOM system tests were made in December 2011. The commissioning program included operation with AC network having voltage rating of 11 kV and 15.75 kV. Typical tests were performed: energisation of the DC equipment, checking that the DC voltage is controlled to its reference voltage, checking hardware and software protective functions for DC voltage equipment. Load tests were performed for both generation and consumption modes. Performances of overcurrent valve protection and operation of cooling systems were checked, and reverse was made. STATCOM dynamic performances were tested under operation in parallel with the synchronous compensator.

STATCOM control algorithms implemented in the substation power controller can be described as follows.

1. In the event of a deviation of the total 400 kV lines reactive power flow beyond ± 60 Mvar or a voltage deviation beyond 380 ÷ 420 kV on 400 kV buses, STATCOM will begin to ramp up the power of the required sign at a rate of 10 Mvar/period.

2. In the absence of conditions for ramping up the power, STATCOM ramps down power to zero at a rate of 0.0056 Mvar/period. In this case, there is a redistribution of power between STATCOM and synchronous compensators independently of each other in accordance with their control algorithms.

7. FAILURE PROCESSES WHEN ENERGIZING UNLOADED CONVERTER TRANSFORMERS

In 2013 there were two emergency shutdowns of HVCU-4 when unloaded converter transformers were energized. It is known that the energizing of power transformers is accompanied by slowly decaying inrush current, the magnitude of which depends on many factors. Inrush current can cause huge voltage distortions, which result in large firing angles and even commutation failures of valves.

Every HVCU is currently being tripped on/off at least two times a day to provide for the abruptly variable load schedule. Generally, when HVCU is tripped off, the converter transformers remain energized. This solution completely eliminates the problem of inrush currents, but it is not optimal, as it leads to increased energy losses.

There are two possible ways to solve this problem:
1. Reduce the transformer inrush currents (to eliminate the **cause**).
2. Increase the stability of the HVCU to distorted voltage (to fight the **effect**).

The measures listed below are significantly different in feasibility and cost. Some of them can be implemented during the day-to-day operation and maintenance, some of them can be performed during the reconstruction of the substation.

Reducing the magnitude of transformer inrush currents

1. Connecting the transformer via a pre-insertion resistor. This is the only measure that essentially solves the inrush current reduction problem.

2. Individual phase control of transformer connection. The disadvantage of this measure is that, first, the possible residual transformer magnetization is not taken into account, and

second, the same circuit breaker can also switch the capacitor banks as well, which is undesirable.

Increasing the stability of the HVCU when energizing transformers

The protections settings of HVCU-4 equipped with a reverse version of the C&P system (C&P-R) are identical to the protections settings of the C&P systems at other HVCUs. C&P system of HVCU is equipped with a protection that prevents the rectifier (inverter) from long time operation with large firing angles exceeding the setting values.

This protection at the HVCU-4 mainly triggers due to the presence of additional capacitor banks on the commutating voltage buses that move the first pole of the frequency characteristics of the network to the lower frequency zone.

To reduce the probability of operation of this protection, it can be recommended to:

1. Arrange the equipment switching philosophy so as to avoid switching of additional capacitor banks on tertiary windings of working HVCUs when energizing the converter transformer.

2. Transfer the on-load tap-changer to the manual control mode and set the rectifier firing angles at the level of $11 \div 13^0$ before energizing the converter transformer.

Both of these measures reduce the probability of operation of this protection at the rectifier, but do not affect the operating conditions of the inverter side. Analysis of oscillography charts has shown that in the case under consideration at the time of tripping the inverter firing angles (β) were reaching up to 51-53°, which is merely 2-4° lower than the inverter protection triggering setpoint.

It can be recommended to revise the technical specifications for HVTV with the purpose of increasing the allowable loads levels and increase the protection settings both for firing angles level and overload duration. This recommendation can be performed during the reconstruction of the substation.

From the measures listed above, the switching order of additional capacitor banks can be recommended for prompt execution.

8. FAILURE STATISTICS

Since 2003 and to 2011 inclusive (9 years), cross-border electrical power transmission Russia - Finland operated quite steadily. An averaged electricity export in these years was 10.5 billion kWh per year.

Since 2012, the operating mode of the Vyborg substation has changed significantly. The amount of transferred electricity significantly dropped to 3.8 - 5.3 billion kWh per year on the average for the last 6 years (in 2014 less than 3.0 billion kWh was transferred). Vyborg HVDC back-to-back link is operating with an uneven load schedule, with one or two peaks in the daily load: daytime peak, which is relatively short, and nighttime, more long-lasting.

This uneven loading schedule leads to daily multiple HVCU tripping operations. Recently, there have been 1300 to 1400 tripping operations per year. Undoubtedly, this operation mode makes the equipment operation conditions heavier. Regretfully, no data have been collected concerning the equipment performance degradation due to multiple trips and recoveries. It seems that such materials will become available with time. In particular, it is assumed that frequent cooling and heating of the cooling liquid (deionized water) cause the increase in leakage of deionized water in the valves. In 2014-2016 there were 14-18 cases of leakage of deionized water annually (this is more than in previous years), and in 2017, more than 25.

It is common knowledge that the main equipment of the Vyborg converter station has worked longer than the normal operating period and is overaged. Nevertheless, the reliability of the equipment remains relatively high. There are not so many emergency-caused or forced trips of the main equipment. According to the outage statistics for 2007-2016, HVCU average forced outage rate is 4.9 per year. The main cause of failures is leakage of de-ionized water out of the cooling system of thyristor valves, which needs improvement.

9. FUTURE DEVELOPMENT

Reconstruction of Vyborg HVDC back-to-back link is scheduled for the near future with replacement of the overaged equipment. For many years JSC "NIIPT" have been working on analyzing the outages of the equipment of Vyborg converter station and developing recommendations to improve its operation reliability, which should be implemented with the planned reconstruction.

Thyristor valves and reactive power compensation equipment are scheduled for replacement. Improving the protection of filter capacitor banks is planned. It is also required to develop and implement a protection system including diagnostics of capacitors, which will detect internal failures, such as blown fuses. To protect the control circuits from interferences, it is necessary to replace the C&P to control board circuits with fiber optics. It is also planned to carry out a comprehensive reconstruction of the cooling system.

10. CONCLUSIONS

The paper summarizes the results of the development and modernization of the Vyborg converter station equipment over the last 10 years aimed at increasing its functional capacities and reliability.

An automated switch-over of one of the converter units to a dedicated overhead line 400 kV was implemented, control and protection systems were improved, as well as substation power controller. Algorithms were introduced to terminate the voltage collapse with short-circuit ratio reducing in the inverter connection, a method and devices for power reversal were developed and tested in real conditions. Appropriate adjustments were made to the power control system to implement the frequency load shedding algorithm. The power control system was also adjusted in connection with the introduction of STATCOM equipment with a capacity of 50 Mvar. The STATCOM demonstration project was commissioned into operation in December 2011. To improve the reliability of the HVDC link at energizing of unloaded converter transformers, some recommendations were developed. Failure statistics of the converter substation equipment are provided. Recommendations for increasing the reliability characteristics, which should be implemented with the planned reconstruction, are given.

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