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A Live Black-start Capability test of a Voltage Source HVDC Converter

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SUMMARY

This paper describes the preparations, execution and lessons learned from a live black-start test conducted on 19th of November 2014 with the Voltage Sourced Converter (VSC) HVDC link Skagerrak 4. The test was performed during the commissioning period of Skagerrak 4. Three silicon furnaces at the Eramet processing plant in Norway, each with an operating power of 30 MW, were energized from the Danish grid using the Skagerrak 4 HVDC link and a small isolated a.c. grid in Norway.

The black-start was successfully executed as a result of detailed planning and preparations, including PSCAD studies and temporary adjustment of protective settings. Among the special challenges were the low short circuit fault current from the VSC, coordination between all parties involved in the test and restoration to normal operation after the test was completed.

The full-scale test of the technology and procedures demonstrated that today's VSC based HVDC links with high power ratings can be utilized not just to support restoration after blackouts, they can also energize and supply isolated a.c. grids with substantial loads fully independent of local generation.

KEYWORDS

HVDC power transmission, VSC, Blac-start, Islanded Grid, Commissioning

1. Introduction

Skagerrak 4 is the fourth HVDC interconnector installed between Kristiansand substation in southern Norway and Tjele substation Jutland in Denmark. Skagerrak 1-3, which were installed in 1976, 77 and 93 respectively, utilise Line Commutating Converter (LCC) technology. Skagerrak 4, with a nominal power capacity of 700 MW, was commissioned in 2014 and utilise VSC technology with inherent black-start capability.

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Black-start is the procedure to recover from a total or partial shutdown of the transmission system, which has caused an extensive loss of supplies. Among the advantages of choosing HVDC with VSC converter technology is the ability to energize and stabilize an a.c. grid during restoration after a blackout with its full power capability and few operational restrictions.

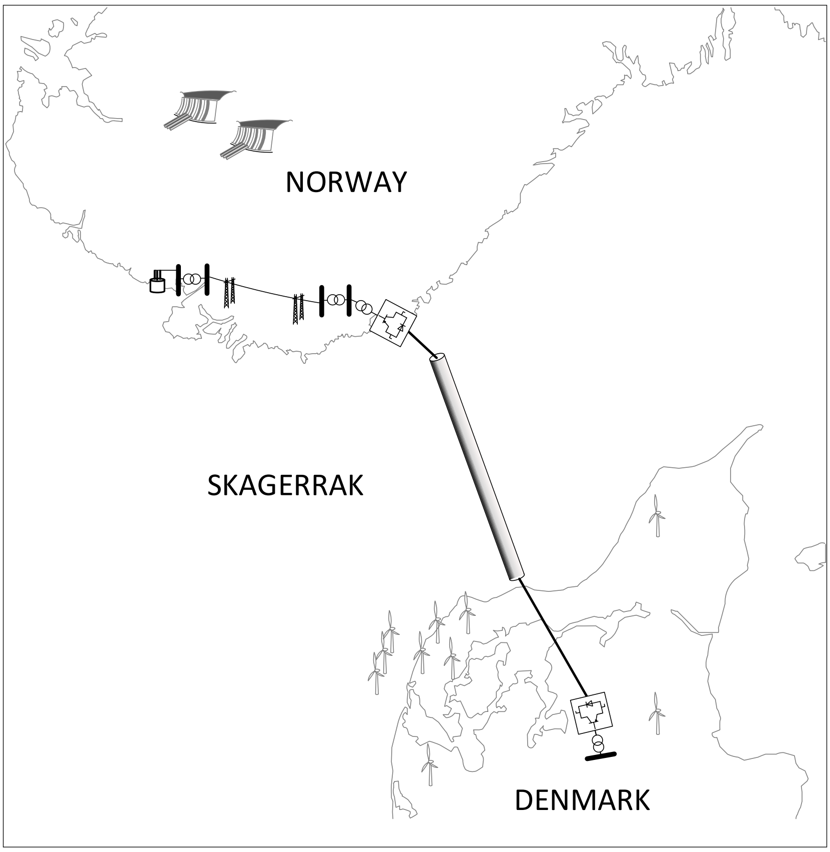

Figure 1: Skagerrak 4 HVDC Link with Black-start test grid

During the next decade, the Norwegian Transmission System Operator (TSO), Statnett, is planning to install two new 1400 MW VSC HVDC links, one to Germany and one to UK. The existing 700 MW Skagerrak 4 link and these planned 1400 MW links will result in a combined VSC power transmission capacity of 3500 MW from Norway to neighbour countries. This is a significant transmission capacity compared to the total power generation capacity in southern Norway.

Norway and the Nordic countries have a de-regulated energy market, in which Statnett does not directly control the domestic power generation. In Norway, several aluminium smelters are located in close electrical proximity to the VSC converter stations in the transmission grid. Fast restoration of the power supply after a blackout is of uttermost importance for these smelters. The VSC based HVDC links will be beneficial in the case of blackouts as they provide the possibility of fast restoration of power supply to the smelters from three potential countries. (i.e. Denmark, Germany and UK).

There are some experiences with black-start of VSC HVDC interconnectors [1]. The black-start functionality has been utilised for each energisation of offshore oil and gas platforms as well as wind farms. Test with use of VSC HVDC as initial power source for start-up of a main power plant has also been performed in the past [2]. However, a start-up scenario where substantial loads and parts of a national transmission system is energised and supplied by the HVDC link has not been performed previously.

To ensure that the different practical operational aspects of the black-start function of a VSC are considered, a live black-start test was performed during the commissioning of Skagerrak 4. Substations in the Norwegian transmission grid are equipped with double busbars. This redundancy enabled Statnett to establish a transmission path from the Skagerrak 4 connection point at Kristiansand to the silicon furnaces, disconnected from the remaining Norwegian a.c. grid. Hence, the silicon furnaces in Norway could be energised and supplied with power transmitted from Denmark, using the Skagerrak 4 HVDC link. This paper shows the preparation, results and lessons learned from this extensive black-start test.

2. VSC technology and the black-start capability

LCC HVDC converters do not have an inherent black-start capability. This capability can be achieved for an LCC solution as well, but it requires synchronous condensers and limited time with near-zero power transmission after de-block of the thyristor valves. The introduction of VSC has removed these obstacles and limitations. Combined with increased power ratings, the VSC converter is an ideal standby technology for black-start and restoration of a.c. grids [1].

During black-start with a VSC HVDC link, the converter at the healthy a.c. grid side controls the cable d.c. voltage. The islanded converter converts the d.c. voltage into a controlled a.c. voltage by switching in the valves [3]. The full converter capacity can then be utilised to support the a.c. grid with both reactive and active power during restoration. The fast voltage control by the converter reduces voltage dips during energization, and overvoltages as the grid is gradually expanded during the restoration process. The VSC converter station acts as a strong and fast support point for the islanded grid in terms of reactive power.

The islanded grid connected to the VSC is connected to the healthy grid on the other side of the HVDC link when the converters in both ends are de-blocked. The required active power to maintain frequency on the islanded side of the HVDC link is imported from the healthy grid and any surplus power in the islanded grid is exported. Hence, the healthy grid can be utilised to balance the islanded grid during restoration. This reduces the need to balance generation and consumption in the islanded grid, which will significantly speed up the grid restoration process after a blackout.

3. Increased capacity and new demands

The ratings of the first HVDC VSC technology schemes were in the range of 10's of MW or lower [4]. Black-start and the ability to support a.c. grid during restoration was an important functionality already on these power levels. However, as VSC converter capacity has increased substantially, this functionality has also become more attractive and valuable.

From being an important component in the restoration of a local grid with its clear place in the grid restoration plan, VSC based HVDC schemes have become a network component capable of powering entire regions of a country by itself. Black-start capabilities of existing power plants, primarily hydropower in Norway, is supplied and controlled by other parties than the TSO itself. Hence, it is in Statnett, the Norwegian TSO's, own interest to have such capabilities in-house and fully controlled by themselves. A VSC scheme in combination with hydropower plant, with excellent black-start capability, increases the availability of power supply and the capability of control centres to re-establish power supply after major outages.

4. Black-start studies and protection adjustments

A detailed model in the simulation software PSCAD of the VSC converter and several likely black-start networks were performed for Skagerrak 4. The dynamic performance study was performed to optimize the HVDC link performance and ensure safe and stable operation. Normal switching operations as connection of a.c. lines and transformers as well as phase to ground and other fault cases were simulated.

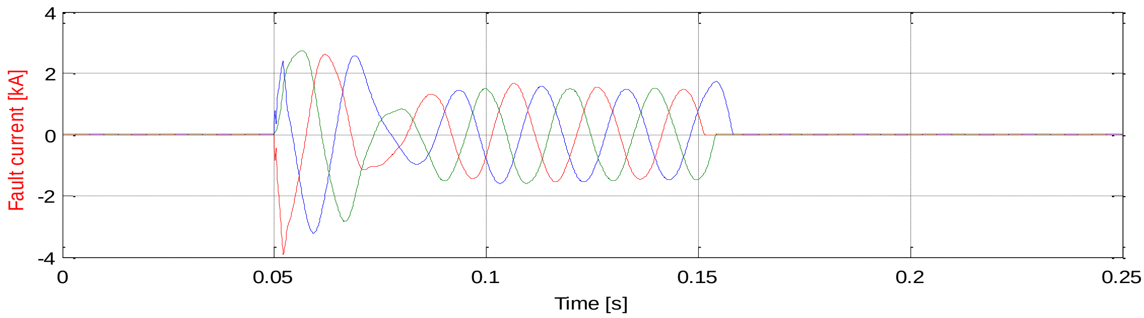

Figure 2: PSCAD simulation of fault current at three phase fault on the Kristiansand 420 kV bus

These simulations showed that the test grid would perform stable operation. In addition, the simulations showed that there was a need to adjust protection settings in the a.c. grid. The short circuit current of a VSC converter is limited by the control system. This is beneficial during normal operation since the connection of a VSC will provide only a limited increase of the dimensioning short circuit power of the a.c. grid. However, for the black-start case, with no other sources than Skagerrak 4, this also means that the thresholds for the a.c. grid protections are not reached during a.c. faults, hindering the protections to be triggered.

To operate safely and according to the Norwegian grid codes during the test it was necessary to adjust the protection settings in accordance with the simulation results. The grid code in Norway requires that every busbar, overhead line, transformer etc. is protected by two independent protection schemes.

During normal operation the 420 kV bus in Kristiansand is protected by current differential protection. The simulations studies reviled that the differential protection could not be used as primary protection with the VSC as the only short circuit contribution, and was replaced by an under voltage protection located in the VSC control during the test. As back up protection for the 420 kV bus the distance relay at the 420/300 kV transformer T6, was adjusted to detect faults at the 420 kV bus in Kristiansand. The threshold settings of the differential protection of transformer T6 were also significantly reduced to detect faults in the transformer during the test.

Faults on the 300 kV a.c. line between Kristiansand and Feda, are normally detected by a differential protection as a primary protection and a distance relay as the secondary protection. The differential protection could not be used as a primary protection due to the same reason as for the 420 kV bus. The distance relay was promoted to the primary relay and a distance relay at the T6 transformer was adjusted to cover the 300 kV Kristiansand-Feda line. Since there was no need for selectivity in the test grid the two distance relays were extended to also include the 300/24kV transformer T31 at Feda substation.

At the 24 kV bus at the furnaces at Eramets factory, the voltage level is low and hence the current was sufficient high to use original protections settings.

Figure 3 shows the protections that was changed or adjusted for the black-start test. During a real black-start, the intention is that the protection settings in Kristiansand substation should be switched manually from the TSO dispatch centre to the VSC black-start protection settings.

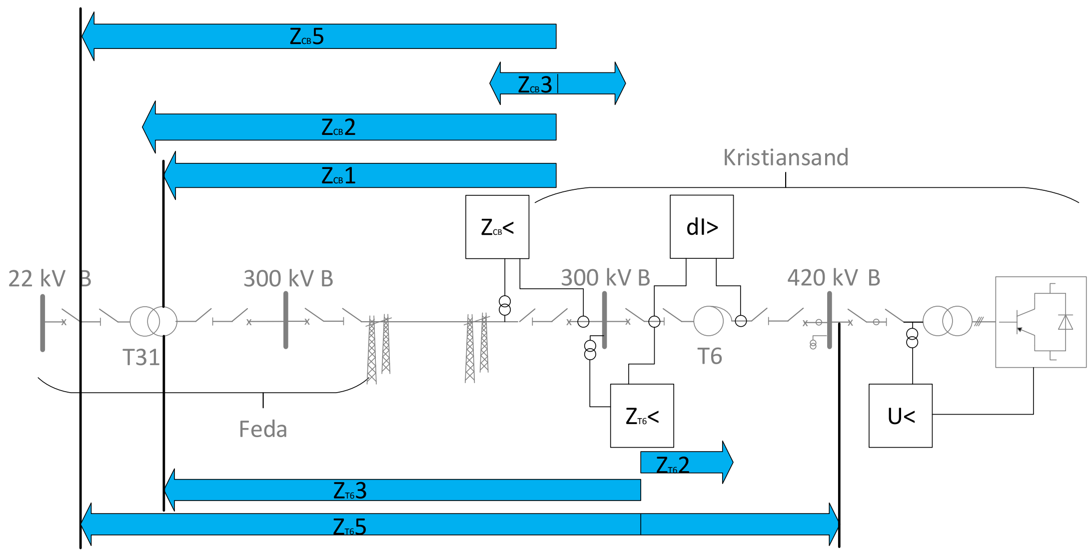

Figure 3: Changes in protection settings for the black-start test, distance relays shown at top of the figure located at the 300 kV breaker bay in Kristiansand, the distance relays shown at the bottom of the figure located at the 420/300 kV transformer in Kristiansand

5. The black–start test execution and results

It is recommended to perform a test of the black-start capability during commissioning of a VSC. This can be accomplished by energizing a de-energized bus connected to the a.c. side of the converter. Such a test is sufficient to evaluate and confirm the substantial functionality of the converter itself, but it would be insufficient for the operational and practical aspects of a black-start. A full-scale live test demonstrates both human and physical obstacles and challenges. It forces both the TSO and the contractor to prepare a black-start procedure, which is safe, easy, efficient and possible to execute during a situation with a major blackout.

The full-scale test for Skagerrak 4 was conducted on the 19th of November 2014 and was mainly executed from the TSO dispatch centre and the control centre at the silicon furnaces. Double busbars, redundant transmission lines and transformers enabled Statnett to perform the test without any outage for customers.

The small a.c. grid used for the test was disconnected from the remaining Nordic a.c. grid by connecting the Nordic grid to one busbar in each station and the other bus to the black-start grid, according to Figure 4. In total four breaker bays at 420 kV in Kristiansand and twenty-two breaker bays at 300 kV in Kristiansand and Feda were disconnected from the test buses to separate the test grid from the Nordic grid. The test grid included the HVDC link with the VSC converters at each side, three transformers and a 132 km long a.c. line between Kristiansand and Feda. To change the active power load and the reactive power balance, three silicon furnaces and three capacitor banks was ready to be operated at the end of the test grid radial.

For a fast execution of the black-start test, the disconnectors in the test grid were connected prior to the test and the operator could conduct the switching by operation of the circuit breakers only. Since the test grid was unsynchronized to the Nordic grid, it was of great importance that the test grid not was connected to the Nordic grid. All disconnectors between the test grid and Nordic grid were therefore locked in open position in the SCADA system at the dispatch centre.

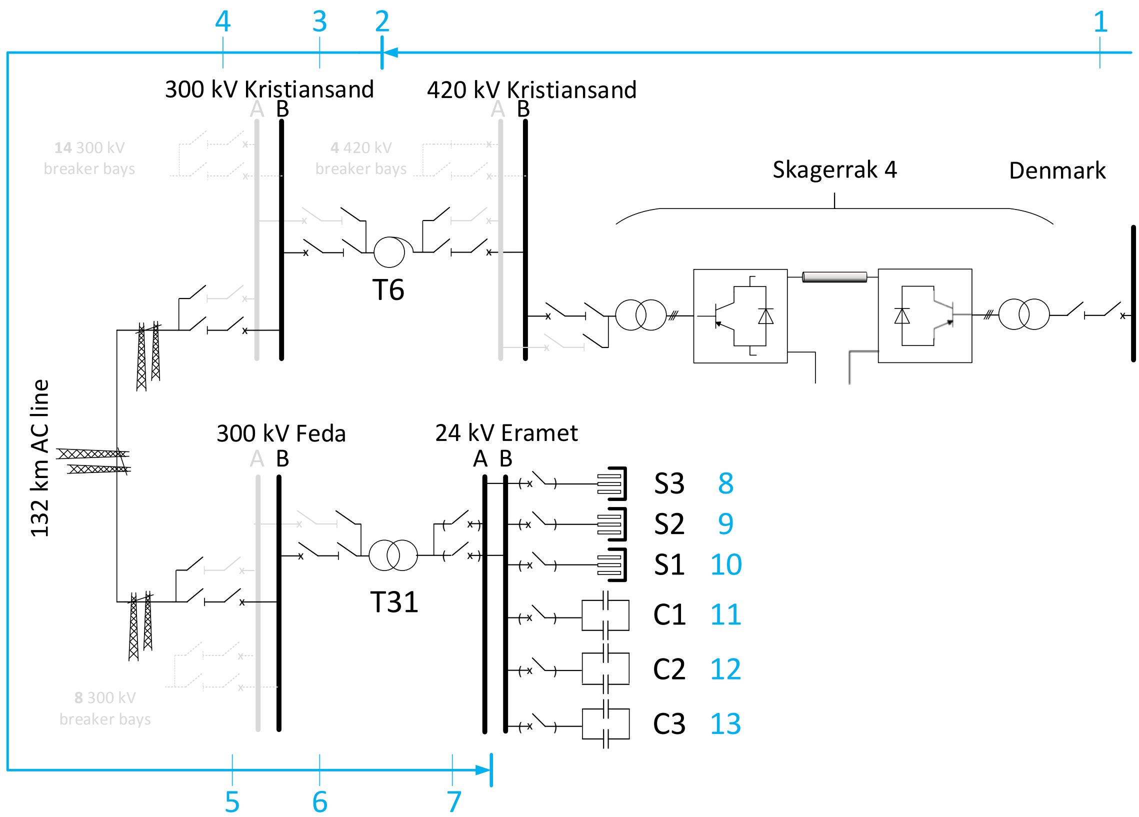

Figure 4: Black-start test grid, the blue numbers corresponds to order of connection

The power capacity available for the Skagerrak interconnection was limited for the duration of the test and distributed on the LCC links. This allowed Skagerrak 4 to be disconnected from the normal grid and connected to the de-energized islanded test grid. Skagerrak 4 was then energized by closing the breakers to the a.c. grid at Tjele substation in Denmark. The Skagerrak 4 converters at Tjele and Kristiansand were de-blocked automatically and thereby energized the islanded a.c. grid connected to Skagerrak 4 in Kristiansand.

Skagerrak 4 was de-blocked in islanded mode and in control of both frequency and voltage of its islanded test grid in Norway. A detailed explanation of this mode of control can be found in [3]. The islanded grid was then extended stepwise by first connecting the 300 kV busbar at Kristiansand substation, the overhead line to Feda and the 300 kV busbar at Feda substation.

The silicon furnace operator Eramet disconnected the furnace S3 from the normal Nordic grid, connected it to the islanded grid and gradually ramped up to full load. After it had been verified that the operation with furnace S3 was stable, furnace S2 and S1 were also connected to the islanded Skagerrak 4 grid, giving a total load of about 90 MW.

Figure 5 shows the transient response in 420 kV a.c. voltage, active and reactive power exchange between the VSC converter station and the a.c. grid during connections and disconnections of furnaces. The results show only minor changes in the 420 kV a.c. voltage at Kristiansand. The steady-state impact on the a.c. voltage is due to the presence of a droop in the VSC converter station a.c. voltage control.

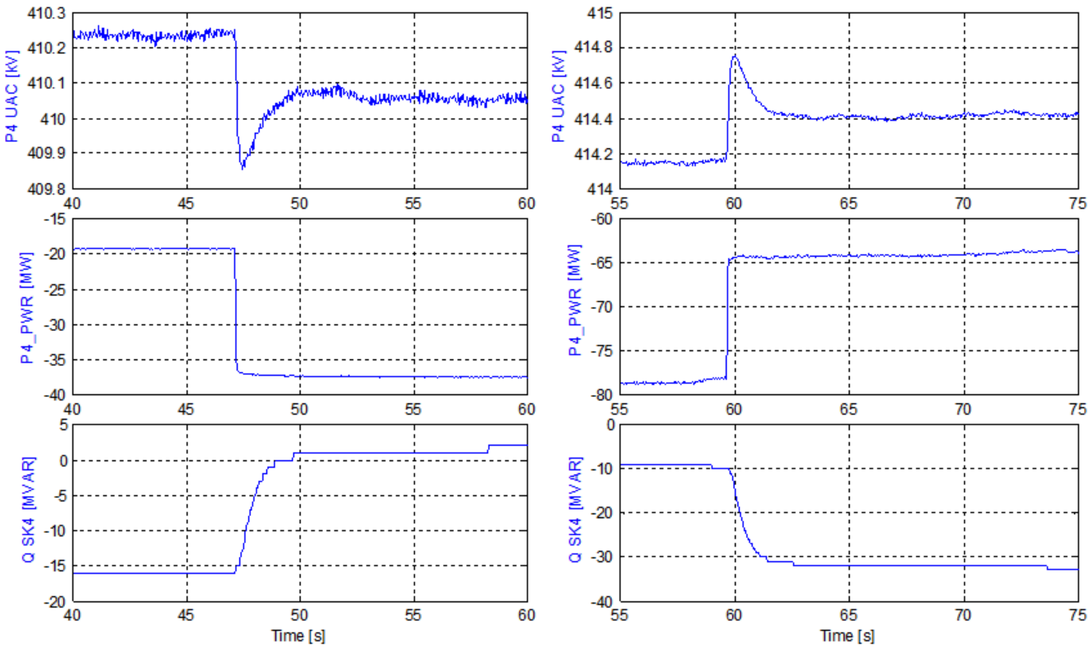

Figure 5: Connection (left side) and disconnection (right side) of load from the islanded grid

The furnaces were powered from the islanded grid for the planned 75 minutes. At the end of this period, it was tested to stepwise connect three capacitor banks each rated 12 MVAr at the 24 kV bus in Eramets factory. Figure 6 shows the response from the VSC converter to the capacitive load changes. The results show that reactive power generation from Skagerrak 4 is reduced and the a.c. voltage is affected due to the droop in the a.c. voltage control. The electrodes are operated with a constant current at 120 kA and the increased active power is given by an increased voltage on the 24 kV bus and thereby also for the voltage at the silicon furnaces.

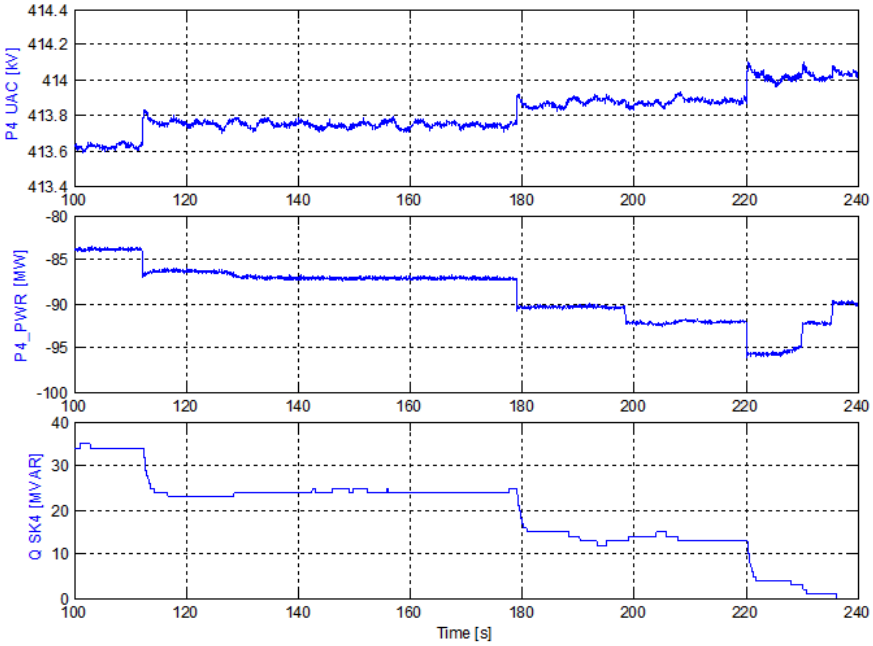

Figure 6: Connection of capacitor banks at Eramet 24 kV busbar

The most obvious continuation of the test would have been to synchronize the islanded grid to the Nordic grid by connecting them and restoring normal operation. However, at the time of the test, Skagerrak 4 had not installed a frequency droop controller and was not able to adjust the frequency of its islanded grid. Synchronisation to the Nordic grid frequency could not be done and it was accordingly not possible to merge the islanded grid with the rest of the Nordic grid without de-energise the test grid first. Hence, the furnaces and power lines were therefore disconnected one by one from the grid and connected to the normal. The disconnection of load can be seen in the right hand side of Figure 5. Skagerrak 4 was blocked and then de-blocked again after it had been connected to the energized Norwegian a.c. grid and normal operation was restored.

6. Lessons learned

The full-scale black-start test performed in November 2014 showed that the basics of the VSC HVDC black-start functionality functioned as intended. It was possible to establish and supply a load in an islanded grid in the range of 100 MW.

A major outcome of the performed test was the need to closer investigate how to connect different islanded grids to each other once stable operation has been established in the different grids. At restoration outgoing from multiple power sources it must be possible to adjust the frequency of the different islanded grids for synchronised connection. In the Skagerrak 4 project it was very late in the planning phase of the test discovered that this functionality was not implemented and hence it was not possible to test this during the time slot of the black-start test. The implementation of this functionality for Skagerrak 4 has been performed after the completion of the commissioning period.

To ensure safe connection of different islanded grids the a.c. breakers shall have the ability to check for synchronisation before it is closed. The Norwegian grid is equipped with such breakers and with the implementation of frequency droop control at the VSC, Skagerrak 4 will, along with hydropower, be a natural black-start source for restoration of the grid.

Another lesson learned is that you in a conceptual phase of a project with this magnitude may end up with conditions and solutions, which at the time of design seems reasonable and robust, while you during an actual live test reveal that these conditions and solutions are not straight forward for the TSOs. In particular for a real black-out scenario, it is of importance that either a strict plan for restoration is followed or the solution is designed in a robust and forgiving way that allows the use of intuitive and maybe non-optimal sequence by the operator that may slightly differ from time to time.

7. Conclusion

The black-start capability of VSC converters in Norway will be of interest after a blackout locally or of the Nordic power system. The simulations and the execution of the test showed that Skagerrak 4 VSC Converter has the ability to build up, stabilise, support and supply a blacked out islanded grid with significant amount of load. This will greatly speed up the restoration process after a major black out. Due to low short circuit contribution in the islanded grid some changes in the protections in the converter station is needed during the special case of an islanded grid with the converter as the only power source.

The test also revealed that to fully utilise the black-start capability of a VSC, the VSC must be equipped with a frequency droop control and the possibility to adjust the islanded grids frequency to other grids. The merging should been accomplished through closing of a.c. breakers with synchronisation check.

To be able to use this ability timely and reliably, it is of major importance that the steps required before the grid can be re-established from the VSC-converter are as fast, reliable, and intuitive as possible for TSOs. In the future where control centres, e.g. TSOs, shall handle multiple black-start capable VSC's it is a necessity that each separate converter automatically detect the need for activating the black-start mode and as far as possible do necessary switching without intervention from operator. A major blackout will result in a challenging situation, and the converter should require as little attention as possible from the operator. As major blackouts are rare, the need for the converter to act in black-start modus will be limited. Hence, TSOs will not be able to gain enough experience in the use of the black-start modus. The need for large degree of automated sequence combined with simple and intuitive pre-defined steps for achieving black-start mode is an important aspect that should not be underestimated when specifying and designing future large VSC converter with black-start capabilities.

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