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HVDC Black start
Feature and its application

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SUMMARY

In the case of a regional black out, a coordinated effort by multiple entities is needed to restore normal operation. The restoration sequence can take several hours or even longer. The first step is to get generators with black start capabilities back in operation. Once sufficient generation is in operation, transmission lines and substations can be energized sequentially and loads can begin to be switched on. Generation capability must match the connected loads in order to maintain stable system frequency and stay within the proper operating voltage range. With adequate system capacity established the island can be synchronized and interconnected to completely restore the regional grid.

DC links can be used to assist in the restoration process. With the development of the voltage source converter (VSC) technology, the possibility for black start is strongly improved compared to the Line commutated converter (LCC) technology. With VSC, black start is possible without any other sources providing system strength, and there is no limitation operating with zero or close to zero load in the initial phase of the network restoration process.

Full scaled field tests of the VSC black start functionality was first performed in 2007 for the Estlink 350 MW cable interconnection between Finland and Estonia [4]. Recently, the black start feature was field tested in the Mackinac 200 MW Back-to Back (BtB) converter in USA, in the Skagerrak 4, 700 MW, cable interconnection between Norway and Denmark [3], and in the fall of 2015 another full scale test was performed, energizing and starting up a completely passive network, during commissioning of the ÅL-link 100 MW HVDC link between Finland and the main island of Åland.

KEYWORDS

Black start, islanded operation, network restoration, VSC-HVDC

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1. INTRODUCTION

The first commercial high voltage direct current (HVDC) system commissioned in 1954, Gotland Link, had black start capabilities. Gotland Link was based on the Line Commutated Converter (LCC) technology with mercury arc valves. A LCC system requires an AC voltage to support the commutation process, and typically synchronous condensers are used to provide the synchronizing voltage to facilitate the start-up of a LCC converter in a passive network. With the development of the voltage source converter (VSC) technology also came the possibility to energize and start-up a passive AC network through the DC tie without any other sources providing system strength. Full scaled field tests of the VSC black start functionality was first performed in 2007 for the Estlink 350 MW cable interconnection between Finland and Estonia. Recently the black start function was also field tested in the Mackinac 200 MW Back-to Back (BtB) converter in USA, in Skagerrak 4, a 700 MW cable interconnection between Norway and Denmark, and in ÅL-link, a 100 MW cable interconnection between Åland and Finland.

2. BLACK START

What is a black out?

Not often, but every once in a while blackouts occur, and electrical services are lost across an entire region. In this situation black outs are not the more common localized outages affecting only a portion of the distribution system. Localized outages can be caused by high winds or ice storms causing tree limbs to fall onto lower voltage distribution lines which are usually radial feeding power to residential or commercial loads. Regional black outs are more wide spread and generally have complex causes. These causes can result in a chain of events leading to cascading outages of the high voltage transmission grid with its interconnected generation. The transmission system is designed and operated so as to withstand single and even double contingency outages of transmission lines or generators. Occasionally, however, multiple transmission lines may be tripped by protective actions. The interconnected power system can then split up into individual electrical islands struggling to achieve balanced operation and thereby survive. Failure to do so can result in voltage collapse causing loss of load and generation. Generation lost could include traditional power plants, wind farms or solar plants. A mismatch between load and generation causes frequency to deviate from its nominal value. This in turn causes loss of more load and generation leading to system instability and regional black out. Recovery from a regional black out is a delicate and complex process requiring careful coordination among multiple parties taking many hours before full service is restored.

Blackouts are not new

The electrical systems of today have grown from a few modest isolated systems with local generation serving local loads. As industrial, commercial and residential electrification spread, economic and reliability considerations led to increasing interconnection of these isolated systems over a period of many decades. The result has been the establishment of large interconnected electrical grids in many cases spanning international borders. In North America, for example there are five main electrical grids. These are Mexico, the eastern US and Canada, the western US and Canada, Quebec in Canada, and most of Texas in the United States. There are also smaller systems in Alaska and Canada. Similarly Western Europe is divided into three main grids. These are continental Europe, northern Europe comprised of Norway, Sweden and Finland, and the United Kingdom. As in North America, there are smaller systems serving insular loads. One negative side effect of increased interconnection, however, is the potential for wider spread

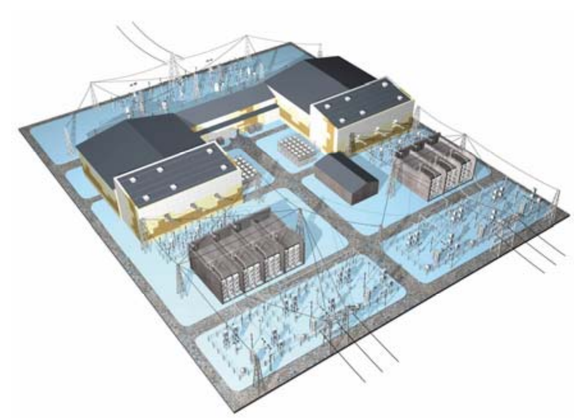

Figure 1. A VSC HVDC station layout in bipolar configuration.

outages should the network become unstable. The probability of such events may be low but nevertheless they do happen occasionally.

In the mid 1960’s the northeast United States and Canada suffered a major blackout. This and the potential for similar events elsewhere led to adoption of additional reliability criteria being to reduce the probability of future occurrences. New practices, rules and regulations in one form or another were widely adopted worldwide. Although these practices no doubt prevented similar events, they did not stop them altogether. For example the western system in North America suffered two major events in 1996. The northeastern US and Ontario suffered a major event in 2003. Similar events took place in Europe during the same year. As a result additional requirements for regional coordination of system planning and operation were imposed by the industry. Furthermore, the increasing penetration of non-traditional renewable generation such as wind or solar power also needed to be taken into account by the expanded grid code regulations.

Putting it back together

In the case of a regional black out, a coordinated effort by multiple parties is needed to restore normal operation. The more widespread the area impacted the greater the need for prioritized coordination between power plant operators, transmission system operators, and load serving utilities. Regional coordination is needed. Situational awareness is essential not only to avoid or limit the scope of such events but also to carefully manage the restoration process in a secure and timely manner. This takes careful advance planning and adherence to pre-established operating procedures. Efficient communication among affected parties is important.

The restoration sequence can take several hours or even longer. The first step is to get generators with black start capabilities back in operation. Once sufficient generation is in operation, transmission lines and substations can be energized sequentially and loads can begin to be switched on. This process requires a careful balancing act. Generation capability must match the connected loads in order to maintain stable system frequency. Voltage support capability must match the requirements of the connected load and the energized grid to stay within the proper operating voltage range. Failure to do so could result in having to start the restoration process all over again. With adequate system capacity established renewable generation can resume its normal operation. Once various operational islands are established, they can be synchronized and interconnected to completely restore the regional grid. Anything that can be done to limit the outage extent or ease return to service should be considered.

Help has arrived

System restoration involves use of black-start generation. It can also involve connection to an intact neighboring grid. If the neighboring grid is asynchronous and operates independently the boundary between the two grids is clearly defined, e.g., the border between Quebec and New England and New York. The networks may still be interconnected asynchronously, however, by direct current (DC) links. The DC link serves as a “firewall” between the two grids so a blackout in one network will not affect the other. The interconnection itself may be lost, but the outage cannot propagate across the asynchronous boundary. In this case the DC link can be used to assist in the restoration process. If the DC link utilizes advanced voltage source converters, such as ABB’s HVDC Light®, the DC terminal connected to the grid suffering the blackout can be started even with a dead network. The DC link then controls the frequency and voltage even without local generation, and can serve load up to its rated capacity.

If the DC link is internal to the grid, system separation may not occur along a readily predictable path. A special protection system can be devised to sense an impending blackout and limit its extent thereby controlling the path of separation. Such a scheme could be designed to ensure a well-defined separation boundary effectively ensuring that one terminal remains energized and available for black start. Alternatively, the VSC based DC link could be connected to a designated power plant with black-start capability in another restoration zone for an extended black start range.

The same approach could perhaps be said to apply to AC lines. The advantage with the VSC based DC link, however, is that it can control the AC system voltage and provide dynamic voltage support during the system restoration process. The DC link can pick up a dead bus or a live bus without any need for synchronization. Furthermore, power flow is controlled. Therefore, the HVDC connection is not subject to overload or large swings in synchronizing power that might otherwise jeopardize stable operation of the assisting grid or generator during restoration. The VSC DC link is not subject to uncontrolled reactive power flows when a large voltage differential appears across its terminals. This distinction can be quite beneficial when reenergizing long AC lines, large substations, reenergizing loads, and synchronization of generation. Strategically placed and intelligently controlled transmission circuits with voltage-sourced converters can offer the system operators additional flexibility during network restoration.

3. VSC TECHNOLOGY

HVDC Light® is the ABB product name for VSC HVDC. HVDC Light® converters are using insulated gate bipolar transistors (IGBT) as the active valve component, and by employing pulse width modulation (PWM) switching patterns the converters can control both active and reactive power, rapidly and independent of each other. The technology has evolved since its commercial introduction in 1997 [5] and is now at its fourth generation utilizing cascaded two-level converters (CTL) as the converter topology [6]. The cascaded two-level converter topology enables the creation of a nearly sinusoidal output voltage from the converter, which in combination with the low switching frequency significantly reduces station losses compared to earlier generations.

With IGBTs both the turn-on and turn-off can be controlled which adds another degree of freedom compared to line commuted converters utilizing thyristors which of only the firing, turn-on, can be controlled. The extra degree of freedom allows the VSC to create and control an AC voltage from charged valve capacitors.

A station layout of a VSC in bipolar configuration is shown in Figure 1, and a simplified circuit diagram of a VSC in symmetric monopolar configuration is shown in Figure 2.

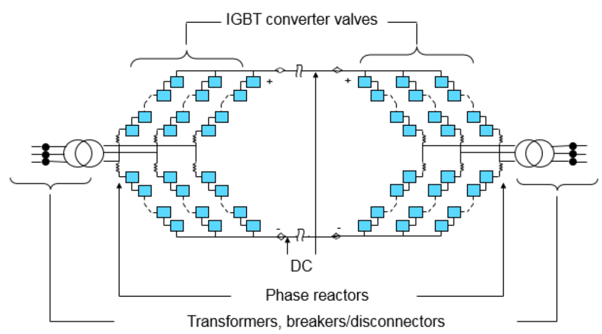

Figure 2: Simplified single-line diagram for a VCS.

4. BLACK START SEQUENCE

A VSC-based converter system is designed to regulate the DC power flow at one station and the DC voltage at the other station. Each converter terminal can also independently of the DC power flow, i.e., the active power flow, control the reactive power. The reactive control can be set to either regulate the reactive power flow or the AC voltage. In this mode the converter controls are synchronized to the AC bus voltage via a phase-locked-loop (PLL). During a black start condition with a passive network the VSC must effectively act as a large uninterruptable power source to balance the loads in the system. During such conditions a different mode controlling the AC voltage amplitude, phase, and frequency is used. It can be referred to as “phasor control mode” or “synchronous machine-emulating mode” since the converter acts similar to a synchronous machine but without physical inertia. This control mode is also used in extremely weak or isolated ac networks.

In the event of a blackout at one end of the converter system the affected station will lose the auxiliary power source. The station batteries will supply essential loads and a small station generator will supply the standby power to the valve cooling system. The first step in the restoration process is to energize the DC side from the other end charging the valve capacitors. When the valve capacitors are charged the converter can be deblocked in black start mode. At this time the converter is controlling the AC bus voltage and frequency. The auxiliary power is restored and the station generator is no longer needed. The only current flowing out of the converter is the current needed to accommodate the auxiliary loads of the station, i.e., house load operation. Figure 10 demonstrate a field test of a converter deblocking in black start mode and restoring the AC bus voltage to its nominal value. A VSC has no restriction operating with a low or even zero current output which simplifies the restoration process compared to a LCC which has limitations operating at low power levels. After the converter is deblocked in black start mode the restoration process can proceed which typically follows a predefined step by step plan that includes energization of AC lines and transformers to pick up loads and start generation plants, and since the VSC controls the amplitude, phase, and frequency of the small island it can easily be synchronized and connected to a larger system.

5. BLACK START FIELD TEST

ÅL-link

ÅL-link is a 100 MW HVDC Light® interconnection between the main island of Åland in the Baltic Sea and the Finish mainland.

Figure 3. ÅL-link – Interconnector between Ytterby (Åland) And Nådendal (Finland).

The main purpose of the link is to serve as a back-up to the subsea AC connection between Sweden and Åland. Because of the increased transmission capacity the link also allows an expansion of renewable generation on Åland.

The HVDC Light® system incorporates special features such as active AC voltage support providing greater network stability on Åland and a unique black start capability which provides faster grid restoration in the event of a blackout.

ÅL-link was commissioned in the second half of 2015 and several field tests were carried out, including STATCOM-operation, active power transmission, black start and islanded operation.

Two different tests of the black start function were performed on Åland:

A. Energization of the converter station AC bus and energization of nearby transmission lines and transformers (restoration step by step).

B. Soft start of the complete Åland AC network (no breaker operations).

Test A – Energizing the converter station AC bus and a transmission line

In order to create a "dead" AC network the de-energized converter station in Ytterby and the connecting transmission lines were isolated from the rest of the Åland AC grid.

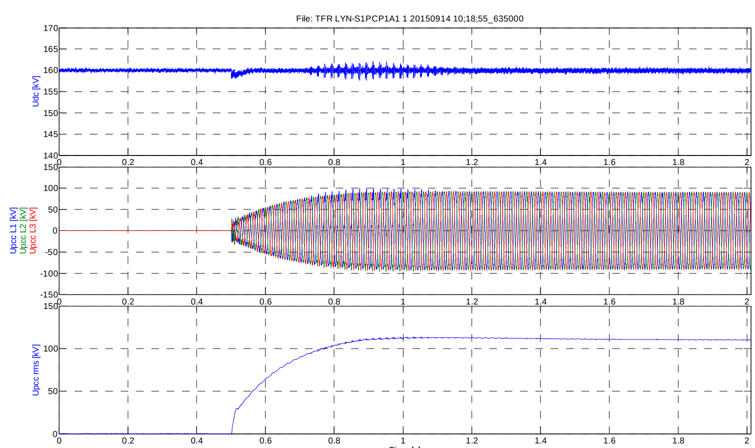

Figure 4. ÅL-link – Energization of the AC-side of the converter on Åland.

The DC side of the converter on Åland was then energized by connecting the already energized DC cables (via the deblocked converter in Finland). The converter is now ready for black start operation.

The converter is then deblocked and the AC side is energized and the voltage is restored by a predefined ramping function, see Figure 4. During the energization small spikes can be observed in the voltages, due to temporary saturation of the converter transformer. The converter is operating in house load operation ready to continue the grid restoration process.

Test B – Soft start of the complete Åland AC network.

If ÅL-link is out of operation and the subsea AC cable from Sweden trips there will be a blackout on Åland. Since the breakers in the Åland transmission system are not equipped with under voltage relays, the breakers will stay connected to the grid after a blackout. This simplifies the AC system restoration process and the restoration time can be extensively shorten. A full scale test for this scenario was carried out as part of the system tests in September 2015. It was performed during the night and the connected load was about 20 MW.

The preconditions were the following; converter on Åland de-energized, DC cables energized (from Finland), Swedish AC cable connected.

To obtain a blackout on Åland the cable to Sweden was disconnected to de-energize the AC system.

The diesel generator in the converter station is started in order to supply the station with necessary auxiliary power and the DC side is thereafter energized by connecting the DC cables. The converter AC breaker is closed, i.e., the de-energized converter AC bus is now connected to the Åland AC grid.

By deblocking the converter the AC voltage is restored in approximately 0.5 s and the active and reactive power reach steady state within 1.5 s. At the deblock instance a distortion in the voltages can be noticed, this has its origin in the control system logics and the software was slightly modified after the test. After the converter AC bus voltage is restored the diesel generator is no longer needed and can be switched off.

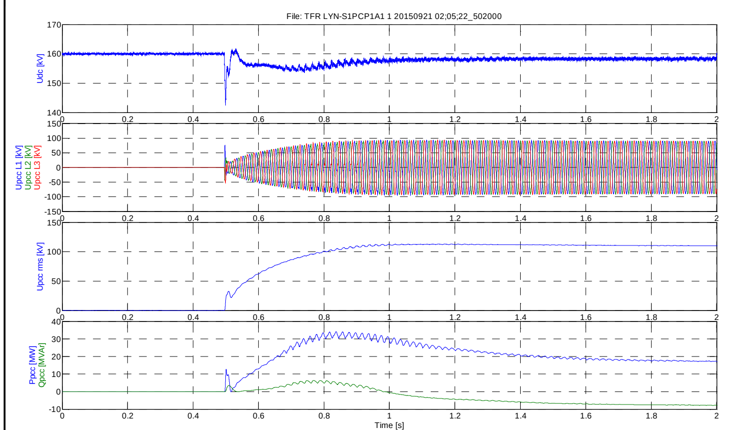

Figure 5. ÅL-link – Soft start of the Åland AC network.

In total the blackout lasted for about five minutes. The time can be considerably shorten by running the sequence automatically instead of, as in this test, manually.

A soft start of the system has several advantages compared to an ordinary restoration process, not only the fast restoration time, but since the voltage is ramped up smoothly transformers, lines and loads are less exposed to switching transients. After the test the Åland AC network was synchronized with Sweden via the subsea AC cable.

As earlier mentioned, active power transmission tests were performed during the system test period. In one of the tests 90 MW was exported to Finland. Since the AC cable from Sweden have a capacity of approximately 80 MW, local generation on Åland was taken into operation in order to supply the local loads and to fulfill the export requirement of 90 MW.

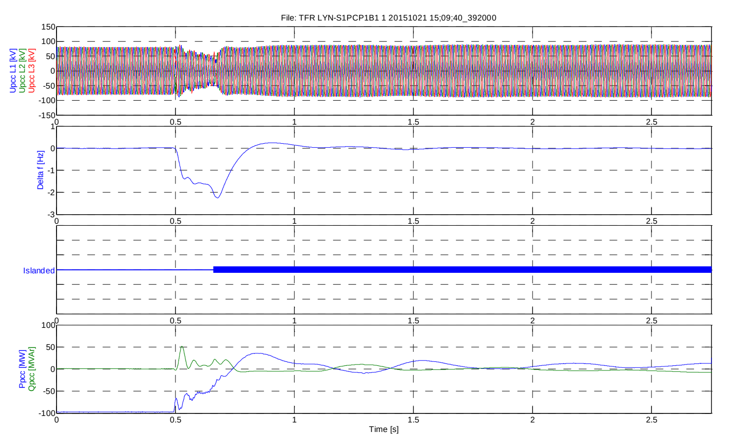

Figure 6. ÅL-link – Islanded network detection, Swedish cable trips at t=0.5 s

During the test a local gas turbine tripped due to overload and as a consequence the AC cable from Sweden was overloaded and eventually the cable relay protection disconnected the cable. Åland is now islanded and ÅL-link still attempts to export 90 MW to Finland which leads to a rapid AC frequency decrease. The control system has a built-in function to detect islanded operation. This function was activated due to low AC system frequency and the control system automatically switched from active power transmission to islanded operation in less than 200 ms following the outage of the AC cable. In Figure 6 it can be observed that the voltage recovery is smooth and stable and that the active power reversal was about 110 MW. The fast response from the link preserved network stability and prevented a blackout on Åland.

Skagerrak 4

The Skagerrak HVDC transmission system comprises of four HVDC links which together provide a total transmission capacity of 1700 MW between Kristiansand in southern Norway and Tjele on Denmark’s Jutland Peninsula. The transmission system operators in Norway and Denmark are Statnett and Energinet.dk respectively. Skagerrak 1-3 are based on LCC technology and were installed 1976, 1977 and 1993. Skagerrak 4 rated 700 MW is based on VSC technology. A number of system considerations influenced the selection of the VSC technology, such as simplified reactive power compensation, improved voltage stability, black start capability, and mitigation of multi-infeed effects from other HVDC links in the region.

Figure 8. Skagerrak 4 – Interconnector between Kristiansand (Norway) and Tjele (Denmark).

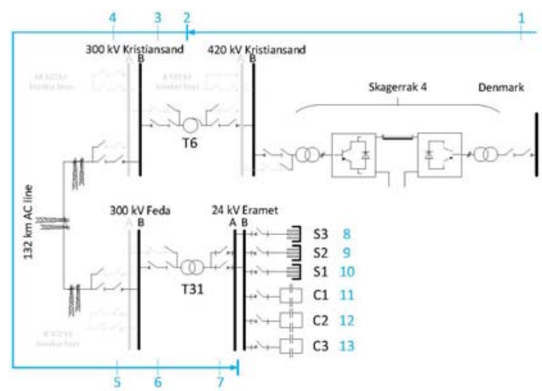

Figure 7. Black-start test grid, the blue numbers corresponds to order of connection.

Commissioning of Skagerrak 4 was performed in 2014 and several field tests were carried out. One test was a full scale system test of the black start feature. Substations in the Norwegian transmission grid are equipped with double busbars, redundant transmission lines and transformers. This redundancy enabled Statnett to establish a small isolated AC system (Figure 7), with three silicon furnaces rated 30 MW each at the Eramet processing plant that was re-energized by Skagerrak 4. The first step was to close the breakers to the AC grid at Tjele substation in Denmark. The converters at Tjele and Kristiansand were de-blocked and the converter at Kristiansand was ready for black start operation. To minimize the inrush current and transients the 420/300 kV transformer (T6) was energized by a soft energization together with the converter station transformer. The islanded grid was then stepwise energized

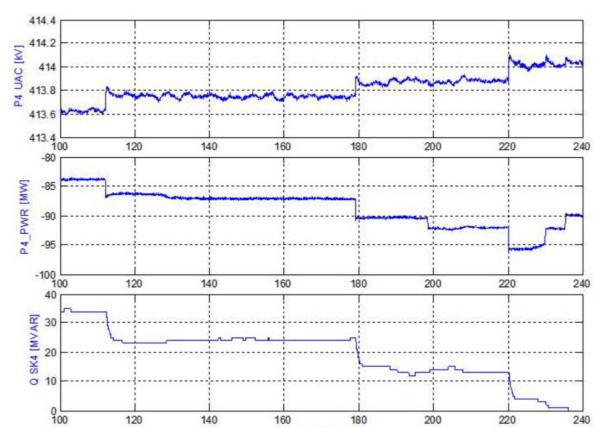

Figure 9. Connection of capacitor banks at Eramet 24 kV busbar.

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 furnaces were connected to the islanded grid and gradually ramped up to full load. After verification of stable operation with furnace S3, furnace S2 and S1 were also connected to the islanded grid, giving a total load of approximately 90 MW. At the end of the black start test the stability of Skagerrak 4 was tested. Three capacitor banks, each rated 12 MVAr at the 24 kV bus in Eramets factory were stepwise connected, see Figure 9.

Mackinac

Mackinac is a 200 MW HVDC BtB flow control device located in the Upper Peninsula of Michigan USA. A limited test of the black start feature were conducted during the commissioning of the project the summer of 2014.

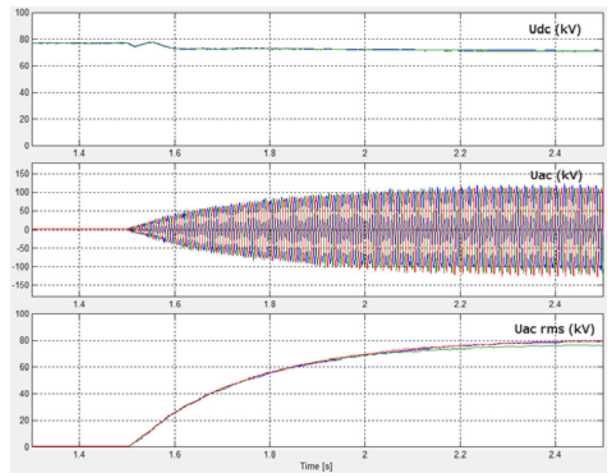

Figure 10. Black start field testing of the Mackinac VSC station.

Two different tests of the black start feature were performed. In the first test the converter was energized from the DC side after which a small isolated system containing a large transformer was black started, see Figure 10. In the other test the converter was operating in constant power mode transmitting active power south to north. An island was created on the north side with the converter as the only source feeding the island. The converter automatically detected the islanded network and changed the control mode from constant power mode to islanded control mode which is used during a black start, i.e., the converter is controlling the AC voltage amplitude, phase, and frequency. After the test the islanded network was synchronized to the main network and finally reconnected. After the islanded and main networks are confirmed reconnected an operator can manually change the control mode back to constant power control mode.

6. CONCLUSIONS

In the case of a regional black out, a coordinated effort by multiple parties is needed to restore normal operation, and the restoration sequence can take several hours or even longer. A HVDC link can assist and greatly reduce the time it takes to restore a network. A VSC can be started in a completely dead network and can control the AC voltage amplitude, phase and frequency. The HVDC link can also assist during the continued network restoration process with its dynamic voltage support, controllability, and ability to connect asynchronously to adjacent grids or to connect a smaller island with a larger system.

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