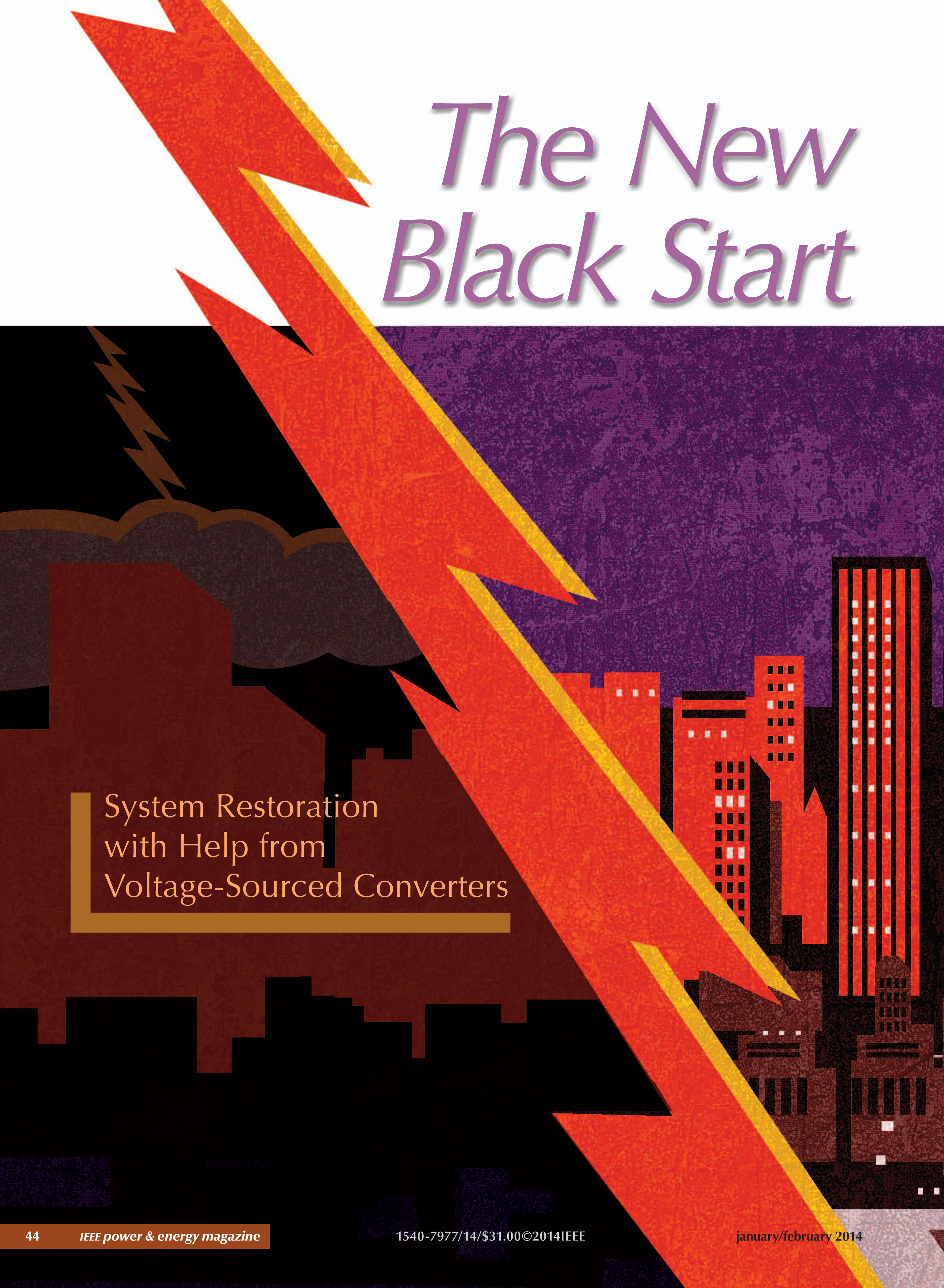
The New Black Start

System Restoration with Help from Voltage-Sourced Converters



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THE VERY FIRST COMMERCIAL HIGH-VOLTAGE DC (HVdc) transmission system, commissioned in 1954, had black-start capability. This system links the island of Gotland in the Baltic Sea with the Swedish mainland. Gotland had very few generating units, and the HVdc system was required to start up and deliver power without any generation operating on Gotland. Because the HVdc stations used line-commutated converters (LCCs), synchronous condensers were necessary to start up the dc system with a dead receiving network. This complicated the start-up sequence for system restoration.

The introduction of voltage-sourced converters (VSCs), with ratings suitable for transmission, has simplified the black-start sequence. Synchronous condensers are not required for operation or for starting VSC-based HVdc transmission. Interestingly enough, the first commercial VSC system, commissioned in 1999 to deliver power from wind generation, is also on Gotland.

Conventional HVdc transmission complements ac transmission for certain well-established applications. These include long-distance bulk power transmission, long submarine cable crossings, and asynchronous interconnections. The controllability of HVdc can help mitigate loop flow, prevent cascading outages, and damp system oscillations. VSC technology has broadened the HVdc application base for use in relatively weak systems, as an outlet for nontraditional renewable generation, and for long underground connections with extruded cables. Operation with weaker ac system interconnection is possible due to the improved voltage stability with VSCs. VSC systems can better ride through under voltage swings while reducing their severity by providing dynamic support. VSCs are self-commutated and can operate indefinitely at zero-power or very low-power transfers. These distinct capabilities enable VSC systems to be used for black starts and to become a more vital component of the system restoration process.

Black Starts with VSC-Based HVdc

The active power control in VSC-based HVdc transmission is assigned to regulate the dc power flow at one station and the dc voltage at the other station. Active power and reactive power can be controlled independently while still maintaining a constant dc transmission voltage. Reactive power control at each station can be selected to regulate either the reactive power flow or the ac voltage. References can be set within predetermined limits by the system operator. During normal converter operation with a strong or relatively strong ac network connection, converters can operate in their standard control mode. In standard mode, the converter controls are synchronized to the ac bus voltage via a phase-locked loop (PLL); the respective real and reactive current orders are calculated in the d-q reference frame and controlled by ac vector current control as the inner most and fastest control loop.

Because VSCs are self-commutated, they do not necessarily require a stiff ac voltage source for stable operation. During black-start conditions, however, the ac network is passive, and no generation is connected. The VSC must then effectively

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operate as a large uninterruptible power supply. Under such conditions, a different fundamental control mode must be used. This mode controls the amplitude, phase, and frequency of the ac voltage so it matches preset reference values. It can be referred to as "phasor control mode." The converter then operates in a manner similar to a synchronous machine but without physical inertia. This mode could also be called "synchronous machine-emulating mode." Variations of phasor control mode are used for black starts, for operation with a very weak ac network connection, for operation with isolated wind parks, and during quasi-islanded or islanded conditions with relatively little or no generation online. During islanded operation the dc terminal independently controls both the ac voltage and the frequency of the islanded network to set reference points, i.e., it provides voltage and frequency control.

In the event of a blackout of the ac grid at one end of the dc link, the station batteries ensure that the control and protection systems continue to function for some period of time, e.g., 30 min, on stored energy. The station may be stopped (blocked) and isolated safely during that time, after which there may no longer be any source of auxiliary power. A small diesel generator would then start up to supply enough auxiliary power to keep the batteries charged and provide stand by power to the converter valve cooling system. With the dc link energized from the remote end in dc voltage control, the dc capacitors at the local end are charged and the converter can be started (deblocked) in black-start mode. The converter station is then controlling its ac output voltage and frequency, thereby restoring station service power for its own auxiliary loads such as cooling pumps and fans. The diesel generator is then no longer needed. VSCs can be operated indefinitely with little or no power or current flow. During such periods, there is no issue with sustained discontinuous current as there is with LCCs. There is therefore no need to rush to pick up load with the VSC. System restoration can be performed in a careful and structured manner, with proper coordination among transmission service providers, system operators, and load-serving entities.

If the dc link interconnects two asynchronous networks, the boundary between them is clearly defined. The dc link serves as a "firewall" between the two grids so a blackout in one network will not affect the other. The interconnection may be lost, but the outage cannot propagate across the asynchronous boundary. If, however, the dc link is embedded in a network, the locus of system separation may not be readily predictable. This suggests use of a remedial action scheme (RAS) or special protection system (SPS) to limit the extent of the blackout. The RAS or SPS could be implemented by sensing out-of-step conditions, impending voltage collapse, under frequency, or circuit overloads. Such a scheme could be designed to ensure a well-defined separation boundary bisecting the dc link so 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 reactive power reserve during the system restoration process. The dc link can pick up a dead bus or a live bus without any need for synchro-check or synchronization. Furthermore, power flow is controlled. The HVdc connection is therefore not subject to overload or large swings in synchronizing power that could jeopardize stable operation of the assisting grid or generator during restoration. The VSC dc link is also 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 and large transformer banks, for cold load pickup, and for synchronization of generation.

Figure 1 depicts a VSC-based HVdc converter station with a capacity on the order of 1,000 MW. Typical reactive power capability for a

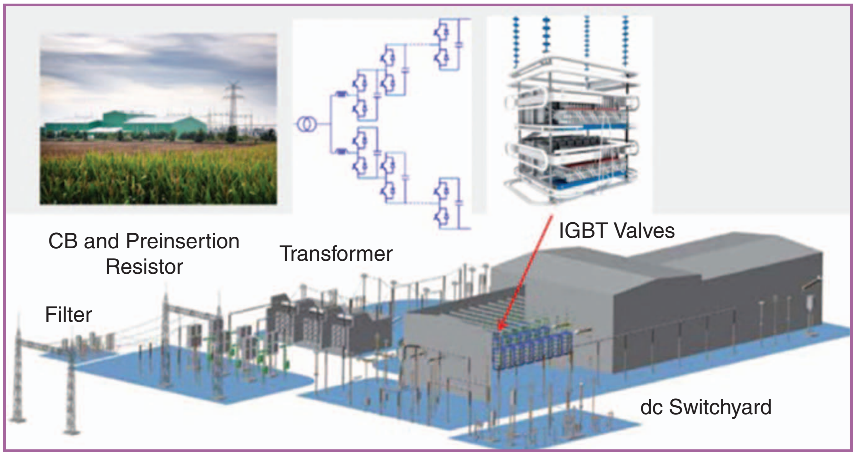

figure 1. A VSC HVdc station layout, 1,000 MW, ± 320 kV (640 kV).

1,200-MVA VSC converter is illustrated in the P-Q diagram given in Figure 2. There is some variation in reactive power capability with ac voltage level. The black "V-shaped" lines in Figure 2 simply represent a 95% power factor reference. The P-Q capability of the converter is similar to the P-Q capability curve or "D-curve" for a synchronous generator.

LCC HVdc Black Start with Synchronous Compensators: The Gotland Experience

As stated earlier, the first commercial HVdc system, commissioned in 1954, linked the island of Gotland in the Baltic Sea with the Swedish mainland. At that time, the 20-MW capacity of the HVdc link exceeded the total load on the Island. Economic dispatch often dictated the shutdown of local diesel generation. This resulted in the dc link serving as the island's sole power supply. Since the dc converters were line-commutated, synchronous compensators were required for start-up and for operation without local generation being online. During operation, the HVdc link matched the Gotland demand by means of frequency control. The synchronous compensators supported converter commutation and controlled the ac voltage. Since that time, the load on Gotland has increased, and the HVdc capacity has expanded to 2 × 160 MW for redundancy. Additional synchronous compensators have been installed. The possibility of running the system without local conventional generation remains, however. In the meantime, significant wind generation has been added on Gotland. The control of the dc link effectively acts to compensate for the variation in wind power with regulating power from the mainland.

The Gotland network, with its HVdc interconnection to the mainland, is shown in Figure 3. The process of starting up the Gotland HVdc link without any local generation follows the sequence summarized below. The simplified circuit arrangement for black start is also shown in Figure 3.

- ✔ Start-up a small diesel generator to supply auxiliary power to the converter station. This ensures enough start-up power for station auxiliaries and keeps the station batteries charged to provide essential power to the control and protection equipment.
- ✔ With adequate auxiliary power established, the starting motors for the synchronous compensators can be energized, the machines brought up in speed, and excitation applied.

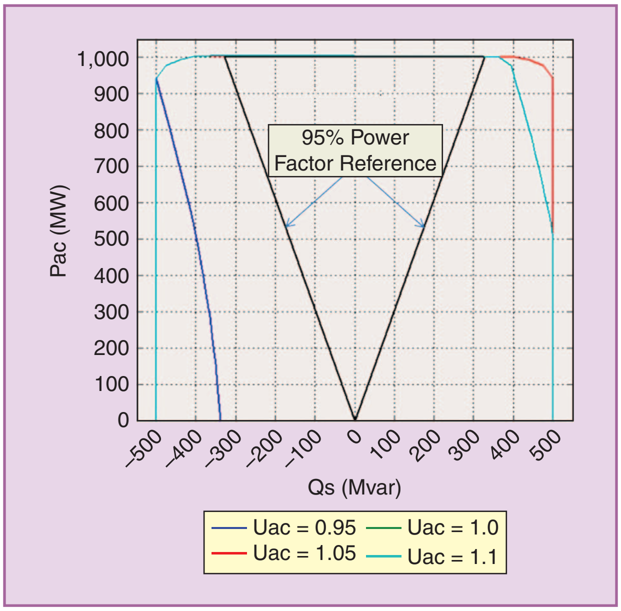

figure 2. A VSC P-Q curve showing reactive power capability, 1,200 MVA/1,000 MW.

- ✔ Once the synchronous compensators provide adequate commutation voltage, the dc converters can be deblocked (started) in frequency control, the compensators brought up to synchronous speed, and the starting motors disengaged.
- ✔ The HVdc link is then able to supply the running power to the synchronous compensators and its own

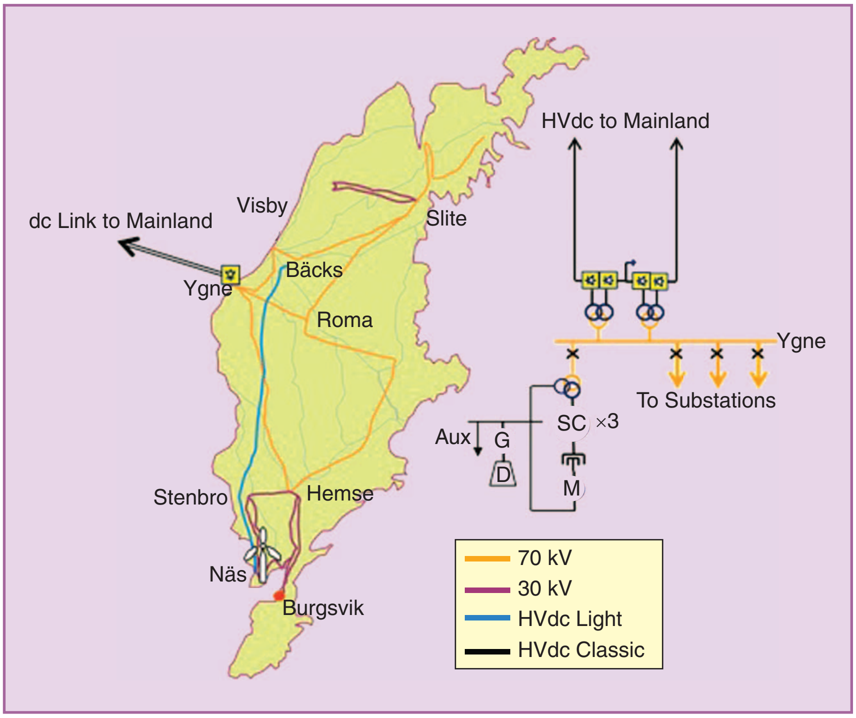

figure 3. The Gotland HVdc, LCC black start with a synchronous compensator.

auxiliary power. This allows the auxiliary power diesel generator to be shut down.

- ✔ The dc power at this stage is very low, supplying only the dc station auxiliary load and losses in the synchronous compensators. With such low dc current, together with its characteristic harmonic ripple, dc current is discontinuous. Refiring of the converter valves during their normal conduction interval is therefore required. Operational time with discontinuous current is limited, so load must be connected within 5 min.
- ✔ Once the dc link is operating with the synchronous condensers, ac lines can be connected, substations energized, and loads picked up in order. This can include providing start-up power for local generation and exciting power for wind turbine generators.
- ✔ As load is picked up, the dc link will increase its power drawn from the mainland to maintain the frequency on the island. The synchronous condensers regulate the ac voltage and provide inertia, helping to ride through disturbances.
- ✔ If local generation is subsequently started, it can be dispatched to a set power level with frequency control maintained by the dc link. Alternatively, the dc link can act like a generator and share frequency control with local generation.

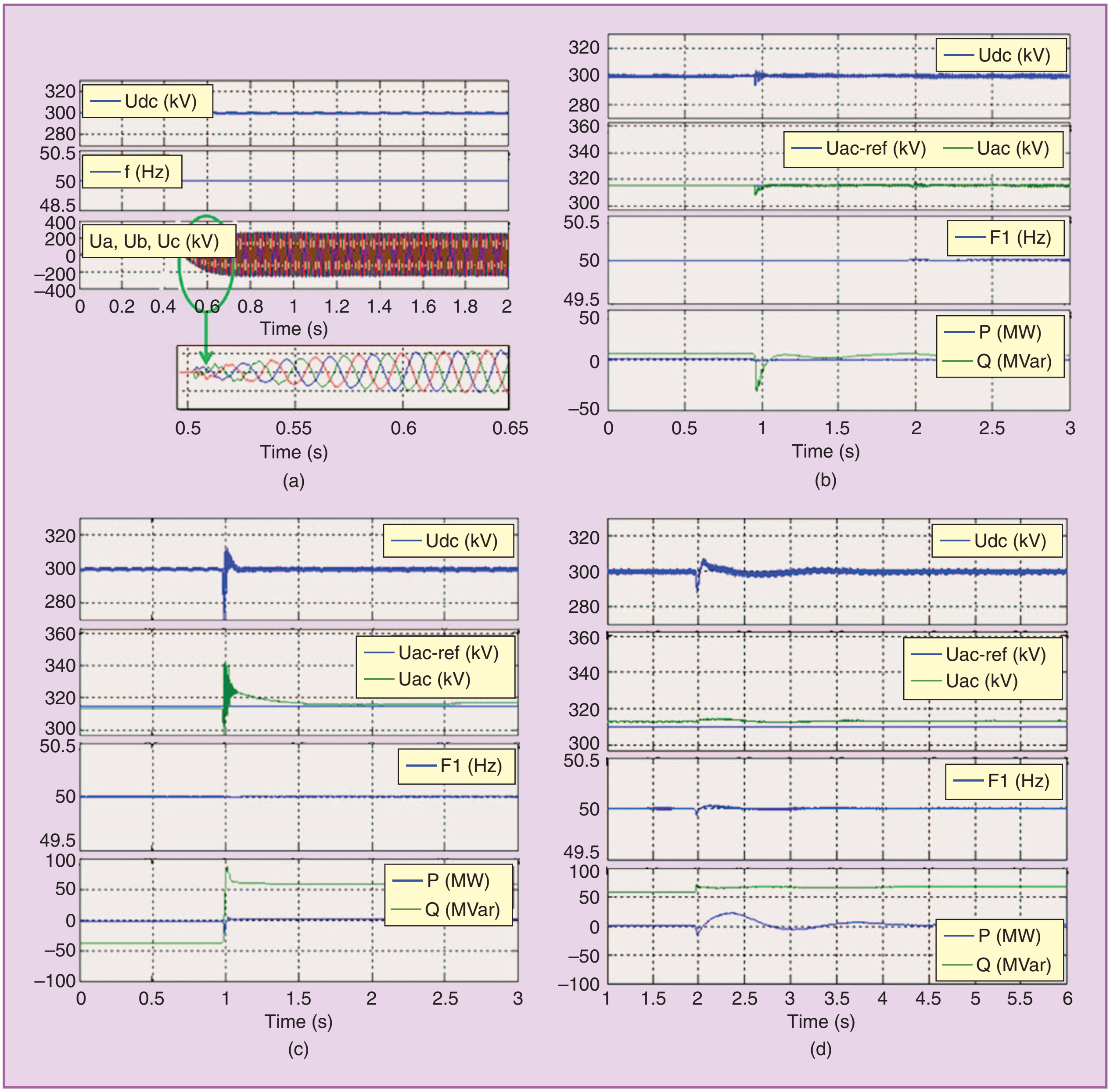

figure 4. (a) Energizing an ac bus from the dc side with a VSC. (b) Energizing a 250-MVA transformer. (c) Energizing a 200-km, 330-kV ac line. (d) Synchronizing a remote 250-MVA generator.

VSC HVdc Black-Start Field Test: The Estlink Experience

Estlink is a 350-MW HVdc cable interconnection between Finland and Estonia crossing the Gulf of Finland. The networks are asynchronous. The HVdc stations contain VSCs. The northern terminal is located in southern Finland, near Helsinki. The southern terminal is located in Estonia, near Tallinn. The system includes black-start functionality. Full-scale system tests of the black-start feature were conducted on the Estonian network during the summer of 2007. The network configuration with double buses, extra transmission capacity, and reserve generation enabled system testing of the black-start function without disrupting consumers.

The black-start tests consisted of starting up the converter from the dc side to energize the ac bus, energizing a large transformer bank, energizing a long ac transmission line, energizing a generator start-up transformer and unit auxiliary loads at a thermal power station, and, finally, synchronizing the unit to the islanded grid here to fore fed solely by the converter station.

Figure 4(a) shows results for the controlled energization of the ac bus by the dc converter. The converter station in Estonia is fed from the dc side, which is energized over the dc cable from the converter station in Finland. The top trace shows the dc voltage being held at its rated value of 300 kV (±150 kV) by the remote station operating in dc voltage control. The second trace shows the frequency being maintained at its 50-Hz reference. The third trace shows the three ac phase voltages at the point of interconnection being ramped from zero up to their rated values by the black-start converter control. The gradual buildup of ac voltage minimizes the converter transformer inrush current.

Figure 4(b) shows results for a local 250-MVA transformer being energized by closing a circuit breaker to the energized bus. The transient effects of the inrush current on transformer energization can be seen in the traces of ac voltage, dc voltage, and converter reactive power output.

Figure 4(c) shows results for energizing a 20v0-km-long, 330-kV ac line from the converter bus, including the dc voltage, ac voltage, frequency, real power, and reactive power traces. Because the capacitive line charging was about 100 MVAr, excess reactive power was absorbed by the converter operating in ac voltage control. The damped line energization transients appear in the ac and dc voltages.

A 25-MVA generator start-up transformer for a 250-MVA thermal power plant was connected at the remote end of the 200-km-long, 330-kV ac line. The temporary increase in reactive power demand due to transformer inrush was supplied by converter reactive power output. Once the transformer was energized, auxiliary load was connected, which allowed the power plant to be started up and then synchronized to the islanded grid heretofore fed only by the dc link. Synchronization of the power plant is shown in Figure 4(d).

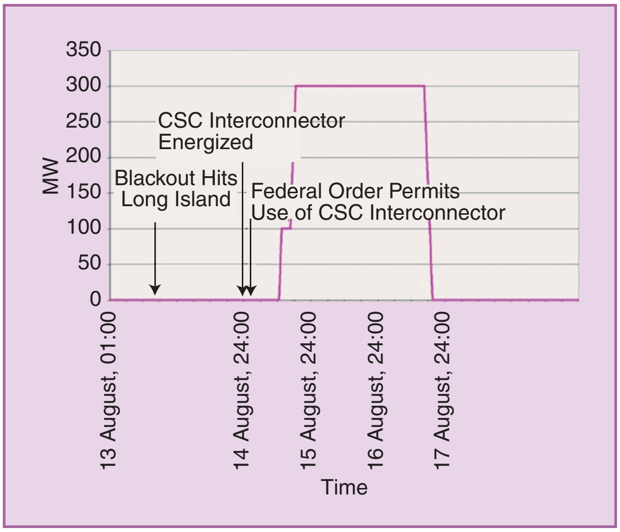

figure 5. The operation of the CSC following the 2003 Northeast blackout.

System Restoration Assistance: The Cross-Sound Experience

The Cross-Sound Cable (CSC) is a 330-MW, VSC-based HVdc interconnection across Long Island Sound between New Haven, Connecticut, and Shoreham, New York. It links ISO New England (ISO-NE) with New York Independent System Operator (NYISO). CSC was commissioned during the summer of 2002. Commercial operation was delayed, however, due to permit compliance issues with the cable burial depth at a few locations. Until this issue was resolved, the CSC remained off-line for about a year after commissioning.

Following the Northeast blackout of 14 August 2003, the CSC was started up under an emergency order from the U.S. Department of Energy. The blackout had left most of upstate New York, New York City, and Long Island without power, but most of New England was unaffected. The HVdc links with the asynchronous Quebec network continued to deliver power to New England and the Maritimes. The CSC was used to help restore service to Long Island, and it was the first Long Island interconnection in service following the blackout. Despite its not being furnished with black-start control, the CSC was able to operate with a minimal system intact on Long Island in the vicinity of Shoreham. In addition to providing power for system restoration, converter dynamic reactive power capability was instrumental in stabilizing system voltage during the restoration process as lines and transformers were energized, generators were restarted, and cold loads were picked up. Dynamic voltage support from the converters operating with ac voltage control helped the system ride through three major disturbance events on Long Island during restoration.

Figure 5 illustrates the power profile for CSC during system restoration on Long Island following the blackout. Figure 6(a) shows the areas restored on Long Island about seven

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hours after the blackout. Figure 6(b) shows the areas restored on Long Island about two hours following the start of CSC.

Offshore Applications

VSC technology has broadened the application base for HVdc transmission to include offshore applications. VSC enables power to be fed from onshore generation to offshore platforms or to the onshore grid from offshore wind generation. Voltage stability is improved, since large concentrations of shunt reactive power compensation are not required. The converters control frequency and voltage for the offshore platform. A VSC is self-commutated and can feed a passive load without any local generation. VSC HVdc has therefore been used to serve offshore oil and gas production platforms with more efficient power generation from shore. VSC-based HVdc links have also been used for generator outlet transmission from remote, high-power offshore wind farms where the use of ac cables or conventional HVdc are impractical. Both offshore applications require specially tailored VSC control methods for getting started and during normal operation. In the case of power from shore, the dc link must be able to start up and feed platform loads with no local generation. In the case of offshore wind plants, the dc link has to feed auxiliary power and exciting power to the wind plant when the wind is either blowing too weakly or too strongly to sustain generation. During normal operation, the link must be able to operate with nontraditional generation, e.g., wind turbine generators with either double-fed induction generators or full-power converters. Offshore applications utilize a voltage-frequency control mode for normal operation, with the converter acting as a constant voltage phasor. With power from shore, the offshore converter acts as an infinite source feeding the production platform. With an offshore wind farm, the converter acts as an ideal slack bus, collecting whatever power is generated. A subapplication of the same control mode is black-start control mode, which is used for initial energization or with zero wind generation.

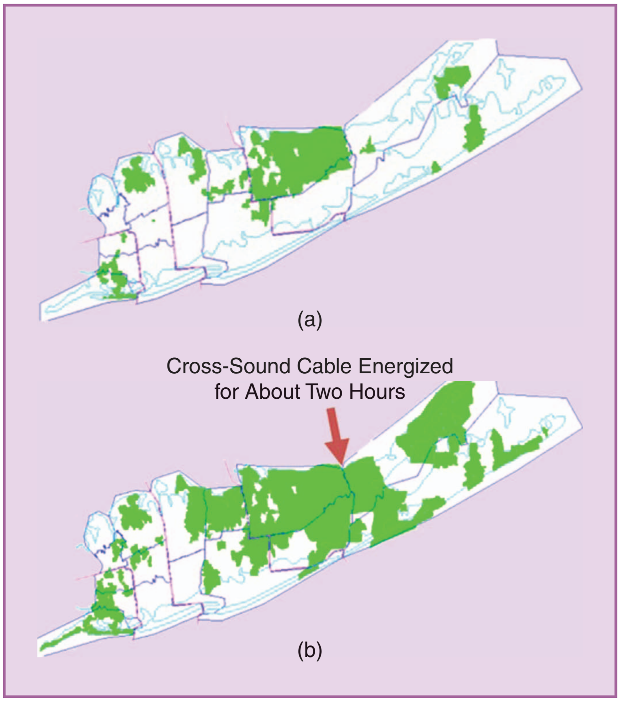


figure 6. (a) Areas restored on Long Island 14 August 2003, 23:30, 7 h after the 2003 Northeast blackout and (b) areas restored on Long Island 10 h after the blackout, on 15 August 2003, 02:30.

Battery Energy Storage: Golden Valley Electric in Fairbanks, Alaska

VSCs can be combined with battery energy storage systems (BESSs) to assist in system restoration. With HVdc transmission, the dc voltage is too high to accommodate a

table 1. BESS performance statistics (source: http://www.gvea.com/energy/bess).

	Outages Prevented	
Year	Total Number of Outages Covered*	Average Number of Prevented Outages per Meter
2003	3	Fewer than one
2004	56	7
2005	34	5.6
2006	82	7.5
2007	65	9
2008	25	2.3
2009	28	2.6
2010	40	3.9
2011	18	1.7
2012	43	2.6

*Outages covered include both local generation and transmission outages and outages due to loss of power from Anchorage via the Intertie.

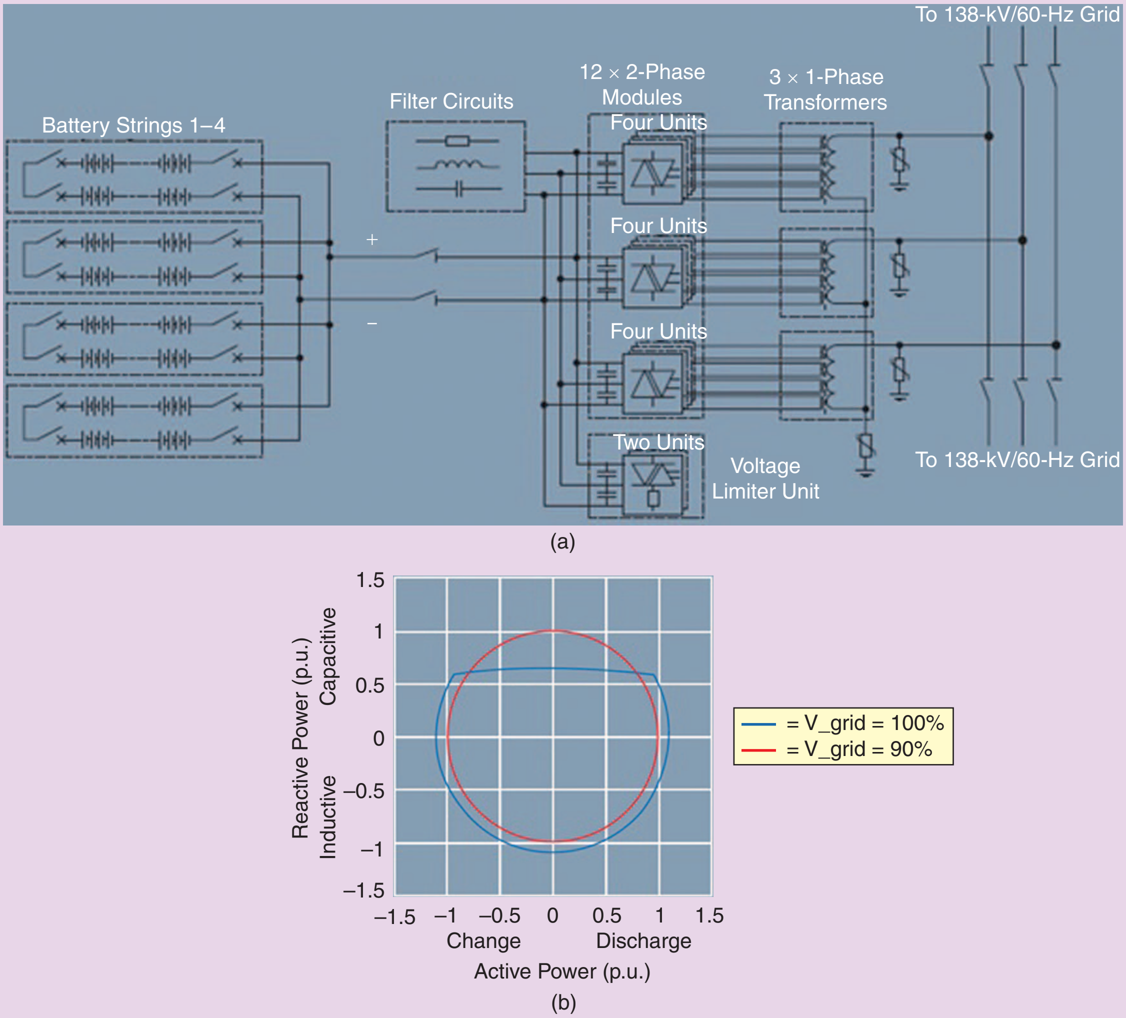
practical battery connection. Static compensators (STATCOMs), however, have a lower dc bus voltage and can more readily be adapted for a BESS application. BESSs can provide ride-through capability and start-up power for system restoration. The associated STATCOM also provides dynamic reactive power reserve for voltage support following contingencies.

Golden Valley Electric Association (GVEA) serves Fairbanks, Alaska, and the surrounding area. Power supply can come from both local generation and over a transmission interconnection between Fairbanks and Anchorage. Critical contingencies consist of loss of local generation or loss of the interconnection to Anchorage. The BESS system improves reliability without having to increase spinning reserve. The BESS can supply as much as 27 MW for as long as 15 min. That is enough supplemental capacity to help serve load while starting up local standby generation following critical contingencies. Table 1 shows the statistical performance of the BESS in terms of outages prevented. A schematic of the BESS electrical system is shown in Figure 7(a). The BESS converter reactive power capability is shown in Figure 7(b).

The Caprivi Experience

The Caprivi link is a VSC-based HVdc interconnection over a long overhead transmission line in Namibia. It links Zambezi in the far eastern part of the country with Gerus in the north central part of the country, a distance of 970 km. The ac networks at the points of interconnection are relatively weak, with long ac lines. System separation is possible, making the ability to run during islanded operation attractive. This can be viewed as a special case of black-start operation with "on the fly" transition to islanded operation.

Figure 8 shows the performance of the Caprivi link during electric system tests in which the ac network at the sending end is opened. The HVdc link detects islanded operation at the sending end and reduces its power transfer to maintain the frequency of



(a)

(b)

figure 7. (a) A basic diagram of the GVEA BESS electrical system and (b) the GVEA BESS reactive power capability, 1 p.u. = 40 MVA.

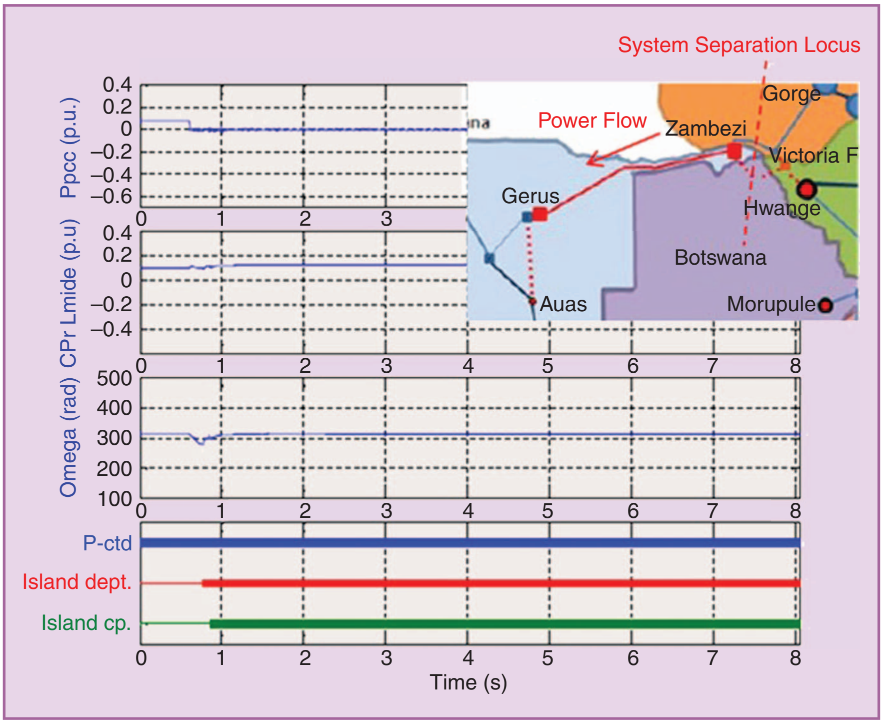


figure 8. The Caprivi dc link with an ac system separation at the sending end.

the islanded network. If more load were connected on the island, power flow over the dc link could actually reverse. In this manner, the dc link remains ready for restoration of the ac interconnection.

Mackinac

Higher levels of wind generation in the north central United States have resulted in increased transmission flows over a broad area. In some cases, increased flows have required remedial action to mitigate circuit overloads. This can have a negative impact on system reliability. A specific case in point is the increased flows on the ac cable connections across the Straits of Mackinac, between the upper and lower peninsulas of Michigan. Remedial actions have included operating new 138-kV transmission lines in eastern Upper Michigan at a reduced voltage of 69 kV or open-circuited. This reduces the loop flow but with the downside of reduced reliability to customers in Michigan's Upper Peninsula (UP). As a long-term solution, American Transmission Company (ATC) saw the need for installing a 200-MW flow control device to manage the inadvertent loop flow. After studying phase angle regulators, variable frequency transformers, and back-to-back HVdc links (BtB HVdc), ATC decided on the latter as the best engineering solution due to its combined capability for power flow control, dynamic voltage support, and black start. The ac network at the planned point of interconnection, however, is relatively weak. This precluded use of conventional HVdc with LCCs at the desired power level. Use of capacitor-commutated converters would have permitted

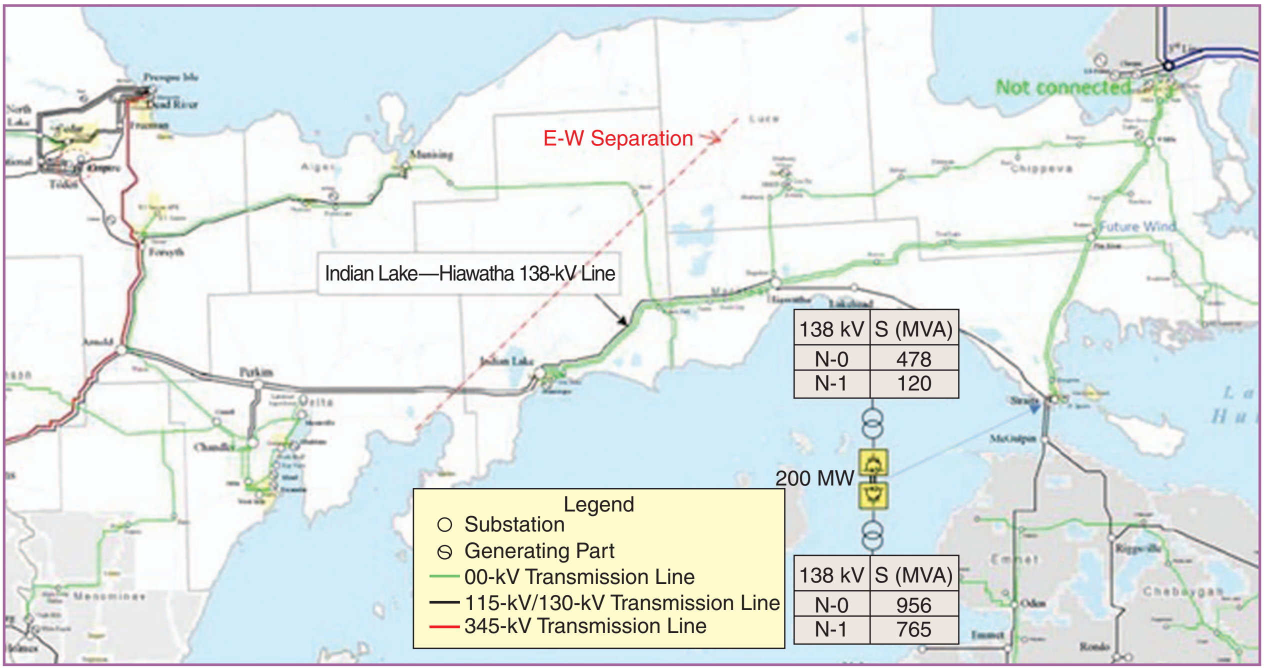


figure 9. The Mackinac 200-MW back-to-back VSC HVdc flow control.

higher power transfers but still not the full 200 MW. Several factors contributed to the use of a back-to-back dc link with VSCs. These included the weak ac connection, the need for dynamic voltage support, the potential for wind generation in the eastern UP, and the possibility of system separation, resulting in islanded operation in the eastern UP, which is not interconnected with neighboring Ontario in Canada. Black-start capability was therefore an important selection criterion.

Installing a VSC-based BtB HVdc link in line with the 138-kV transmission between the upper and lower peninsulas provides the needed flow control, adds dynamic voltage support from each terminal, and permits transmission lines between the central and eastern UP to be closed and operated at their rated voltages. This solves the loop flow problem without degrading reliability. It is interesting to note that Mackinac is a BtB HVdc application embedded in a synchronous network. In other words, Mackinac is not normally an asynchronous interconnection, but it can become one if there is a network separation between the central and eastern parts of the UP following network contingencies. The HVdc link controls are therefore designed to transition smoothly from synchronous to islanded or quasi-islanded operation. Furthermore, to mitigate the chance of cascading outages following loss of transmission lines, the dc link is controlled to automatically alter its power flow in response to changes in the measured phase angle differential across its terminals. This is accomplished by emulating the ac line power flow characteristic. Figure 9 shows the relative position of the dc link in the ac network, along with a possible separation locus.

Conclusions

System restoration from black-start generation resources or by connection to intact neighboring grid locations requires advance planning, careful coordination, and close communication. The more widespread the area affected, the greater the need for prioritized coordination among generators, transmission providers, load-serving entities, and system operators. 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. Anything that can be done to limit the outage extent or ease return to service should be considered. This could include use of VSCs for their dynamic voltage support, controllability, and ability to connect asynchronously to adjacent grids or with intact islands within the larger system. Strategically placed and intelligently controlled transmission elements with VSCs can offer system operators additional flexibility during network restoration.

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