The Impact of HVDC Links on Transmission System Collapse

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ABSTRACT

Modern power systems are continually being expanded, are required to carry more power and are being increasingly interconnected. All of these increase the risk of wide area blackout. In 2003 the North America Blackout demonstrated that a HVDC link provides a ‘firewall’ against the system collapse propagating through a network. The HVDC link between Quebec and New York ensured that the system collapse did not progress beyond the HVDC interconnection interface. The objectives of this paper are to investigate contributions that integrate HVDC interconnections into AC networks. The simulation studies were performed using MATLAB.

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1. INTRODUCTION

The HVDC transmission technologies are playing more important roles in world’s power transmission systems. The use of HVDC technologies can contribute to satisfying these demands. HVDC technologies provide immediate benefits to power grid including bulk power delivery, long distance transmission and asynchronous interconnections.

The 2003 Northeast America blackout suggested that HVDC interconnection provide a ‘firewall’ against system collapse spreading through the networks. This was seen during the Northeast blackout in the USA on 14th August 2003 [1, 2] where around 50 million people were affected by the loss of 61,800MW of load. The commercial losses have been estimated at between $4 billion to $10 billion [4]. The HVDC link between Ontario and New York ensured that the system collapse did not progress beyond the interconnection interface when outage propagated through Qntario and New York [3].

This paper investigates the impact of HVDC constraining system collapse transmitting through the power networks and the influence that HVDC links bring to distance relays. The paper also examined what could happen if the interconnection had been HVAC. In order to investigate certain impact, the 2003 Northeast U.S.A. and Canada blackout will be simulated using MATLAB. A similar power system but interconnected by HVAC line will be modeled for comparison.

1.1. 2003 North America Blackout

On 14th August 2003, Northeast U.S.A suffered from the worst outage event in history [4-16]. The blackout led to about 61,800-MW power lost and affected about 50 million people in Ontario and the eight states in U.S. Northeast. During the event, over 400 transmission lines and 531 generating units at 261 power plants tripped. The outage was inferred by failure of two 345-kV transmission line due to tree contact [4]. The events started slowly, but spread quickly and finally caused widespread voltage collapse in both Canada.

and Northeast United States. The U.S.-Canada Power System Outage Task Force final report [9] gave four causes for the blackout: inadequate system understanding, inadequate situational awareness, inadequate tree trimming and inadequate RL diagnostic support. Figure 1 shows the affected area during blackout [10].

Figure 1. Affected area during blackout [10]

The evidence indicates that distance relays tripping caused the loss of many key lines and accelerated the spread of the cascade. These distance relays responded to overloads rather than faults on the protected facilities [17-22]. Between 16:05–16:10 many 345-kV lines tripped on Zone 3 relays [9, 17-22]. Sammis-Star 345-kV line tripped on relay operation at 16:06:03. Galilon-Ohio Central-Muskingum 345-kV line tripped on Zone 3 relay and reclosed at 16:08:58. The line tripped finally at Galilon on a ground fault. East Lima-Fostoria Central 345-kV line tripped on Zone 3 relay at 16:09:06. Tripped lines led to some generation units become overloaded and tripped as well between 16:09 and 16:10. New York-New England transmission lines disconnected at 16:10:46.

According to ref [9], there were three principal reasons that caused the cascade spread beyond Ohio and caused such a widespread blackout. First, the loss of the Sammis-Star 345-kV line in Ohio led to other transmission lines tripped. Second, many of the key lines were tripped out by the operation of Zone 3 impedance relays. Relays responded to overloads situations rather than true line faults. These relays’ operations accelerated the spread of the cascaded. Third, the relay protection settings may not be entirely appropriate. Relays did not operate as expected during the cascade. Figure 2 shows the apparent impedance inside Zone 3 of the distance protection on the 345 kV transmission line between Sammis and Star [17-22].

However, as a key part of east interconnection, Quebec was not affected by the outage. It is reported that Quebec is connected only by DC ties [8]. During the event, DC links acted as buffers that not allowed disturbance propagate through. Lots of papers have pointed out that HVDC links acted as a stability booster and ‘firewall’ against disturbance during 2003 USA-Canada blackout [5, 11, 14, 23-35].

Figure 2. Zone 3 distance relay operation on the 345-kV Sammis-Star transmission line [17-22]
2. HVDC INTERCONNECTIONS TO PREVENT VOLTAGE OUTAGE

HVDC interconnection can help to prevent cascading outages pass through and enhance power systems. Carlsson [23, 35] reported that HVDC has good controllability of transmitted power. When using HVDC, the power direction can be changed rapidly in a second. With the ability to change the operating point instantaneously so that HVDC can feed/reduce active power into the disturbed system to control the frequency much faster than a normally controlled generator [37]. Carlsson [25, 36] said classical HVDC transmission can vary the power level from minimum load, which normally between 5% and 10%, to max load 100%. He suggested that the DC interconnection could be made to automatically adapt its power flow during outage. The power flow can be limited to protect the network. He also claimed that HVDC can help to reduce voltage oscillations by connecting capacitors or by modulating the station’s reactive power consumption by firing angle control. HVDC transmission link has good performance under connected AC system faults. Such specific actions, like normal power control, emergency power control and voltage control, can help during contingencies. The most important feature of HVDC is that it can never become overloaded [36, 38]. Pan et al [24] claimed that by fast power run-up or run-back control functions, HVDC can help maintain power grid stability. With the ability to control both active power and reactive power, HVDC can provide an effective means of damping oscillations and improve voltage stability. According to [39], when one of the systems has oscillation mode between two generator groups, HVDC has the best active power damping effect if the converter station is electrically close to one of the oscillating generator group. The best location for reactive power damping is the electrical middle point between the oscillating generator groups [39]. HVDC system is provided with power modulation features for stabilization of AC system [37]. With this function, HVDC link can reduce power swing and stabilize the entire system in minimal time.

After the 2003 northeast blackout the North American Electric Reliability Council in its technical report suggested that use HVDC transmission system to improve power networks’ reliability and enhance power systems [15]. Lots of papers [11–33] also suggested the same as well as ABB and Siemens. Loehr [37] has been advocating the breaking up of the two gigantic interconnections or grids that straddle North America into a number of smaller ones since 1999. In his suggestion, these mini-grids can be interconnected by HVDC instead of current AC ties. As Loehr explained, “With ac ties, what happens in one place on the grid affects everywhere else. A major disturbance in Ontario is felt as far away as Oklahoma, Florida and Maine. This doesn’t happen with DC links – it insulates one small grid from the others, but still permits power exchange.”

Nowadays, lots of researchers are investigating the HVDC functions as firewall against oscillations since it was proved in 2003 northeast American blackout. Hafner and Manchen in [14] used the Caprivi Link Interconnector HVDC Light project to study the strong voltage and frequency stabilization function of HVDC function to avoid blackout. By several actual commissioning tests, they showed that HVDC link had good performance under islanded AC networks and normal AC faults. They suggested that HVDC system is able to enhance the stability of extremely weak AC system and to prevent the blackout. [40] examined enhance power system stability through controlling HVDC power flow. In paper [38], Ozerdem and Habboob used MATLAB simulated Turkey to TRNC HVDC submarine interconnection. By comparing VSC-based HVDC and CSC-based HVDC performance under the same applied AC fault, they found that VSC-based HVDC had a better performance than CSC-based HVDC. In 1993 Lee et al [41] suggested to use potential DC system support to enhance AC system in western U.S. Corsi et al [42] discussed the Sardinia-Corsica-Italy HVDC link (SACOI) and the Italy–Greece HVDC link (GRITA) by simulation tests and commissioning results. They demonstrated that using HVDC power modulation can achieve high control flexibility and regulation performance, which are contributing to face unexpected contingencies. Arro and Silavwe [43] discussed what influence a line-to-ground fault occurring on HVDC line will bring to involving AC lines. In order to study the phenomenon, a simulation studies were carried on by PSCAD/EMTDC. A bipolar HVDC connection between the Swedish and Finnish power systems was simulated. Based on simulation work in [43], there was no unwanted tripping in AC lines due to a line-to-ground fault occurred on HVDC lines. Paulinder [44] claimed that an HVDC link has an obvious contribution to power system’s stability during disturbance through modeling CIGRE Nordic 32 system. Du in [45] investigated the VSC-based HVDC control system’s operations under steady-state and different fault conditions. The HVDC link was used different control strategies. Faults were injected at inverter side and converter side separately. It was conclude that for unbalanced faults the voltage dips in the dc-supplied ac system are less severe than in the pure ac system.

HVDC and Flexible AC Transmission Systems (FACTS) were strongly advised in [30–35, 46–48]. As described in [31, 32] ‘FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and for long distance AC transmission. FACTS controllers can, however, also contribute to solve technical problems in the interconnected power systems. FACTS are applicable in parallel connection, in series connection, or in combination of both to control load flow and to improve
dynamic conditions. By these means, FACTS contributes to Blackout prevention too. Therefore, developing large hybrid transmission systems, consisting of HVDC and FACTS, is necessary. Figure 3 gives a brief view of such hybrid AC/DC system. Such hybrid transmission system offers significant advantages in system reliability [32-35]. Performance of AC lines can be improved by FACTS both in transmission capability and reliability. Long-distance bulk power can be transmitted by HVDC. With DC interconnections, high system security could be achieved.

![Figure 3. Hybrid AC/DC system [29-32]](image)

3. DISTANCE RELAY

When fault occurs on a transmission line, the distance relay will protect the line, trip the circuit breaker and disconnect the line from the network [49]. By comparing the measuring impedance with the setting impedance to determine if the fault is inside or outside. If the measured impedance is less than the setting impedance, relay assumes a fault exists inside the protection zone and releases a trip logical signal [50]. Relay is located at the point R. The primary fault current, IF, is transferred to equivalent secondary fault current, iF, via current transformer to the relay. The fault voltage VF is equivalent to the fault current IF product with fault impedance ZF. The secondary fault voltage is achieved by voltage transformer VT [51, 52]. Relay compares the measured impedance, ZM, which is the division of secondary V and I to detect the fault.

\[ Z_f = \left( \frac{V}{V_{Tratio}} \right) / \left( \frac{I}{C_{Tratio}} \right) \]  \hspace{1cm} (1)

\[ Z_m = Z_f \times \left( \frac{C_{Tratio}}{V_{Tratio}} \right) \]  \hspace{1cm} (2)

A typical distance relay has three protected zones: zone 1, zone 2 and zone 3. Zone 1 is always set up to 80% of the protected line impedance. Zone 2 should be at least 120% of the protected line impedance or the protected feeder plus 50% of the shortest following line impedance. Zone 3 is set up to the protected feeder plus the longest following feeder plus 25% of the shortest subsequent feeder or 120% of the protected feeder plus the longest following feeder. Some relays may have up to five protecting zones, some set to measure in the reverse direction [50]. Figure 4 shows a typical 3-zones distance protection.

![Figure 4. 3-zones of distance protection](image)
By comparing the measured impedance with the setting impedance the relay determines if the fault is inside or outside the protected zone [49]. Different fault types have different calculations of the fault impedance. References [49, 53] give the all fault-type calculation formulas.

\[ A-N: U_A = (I_a + k * 3I_0)z_1l \]  
\[ B-N: U_B = (I_b + k * 3I_0)z_1l \]  
\[ C-N: U_C = (I_c + k * 3I_0)z_1l \]  
\[ A-B: U_A - U_B = (I_a - I_b)z_1l \]  
\[ B-C: U_B - U_C = (I_b - I_c)z_1l \]  
\[ C-A: U_C - U_A = (I_c - I_a)z_1l \]

where:

\[ U_A, U_B, U_C \] are a, b, c phase voltage;  
\[ I_a, I_b, I_c \] are a, b, c phase current;  
\[ I_0 \] is the zero-sequence current;  
\[ z_1 \] is the positive sequence impedance of the protected line;  
\[ l \] is the length of protected line;  
\[ k \] is the zero-sequence comparison factor, which could be described as:

\[ k = \frac{Z_0 - Z_1}{3*Z_1} \]  

where: \[ Z_0 \] is the zero-sequence impedance of the protected line.

A full scheme distance relay was modeled as shown in Figure 5.

![Figure 5. Full scheme distance relay](attachment:figure5.png)

![Figure 6. Simple transmission system](attachment:figure6.png)

Zone 2 and Zone 3 timer was set to 200ms and 500ms respectively. The comparing circuits were achieved by block-average comparator\(^4\). The modelled distance relay was tested in a simple transmission system as shown in Figure 6. A 500kV, 5000MW AC network transmitted power to a 500kV, 4000MW load through 3 40-km transmission lines. The relay located to protect first 40-km line. Zone 1 was set to 80% of the protected line. Zone 2 was set to 120% of the protected line. Zone 3 was set to protect whole line.
Relay settings were shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Relay Settings</th>
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</thead>
<tbody>
<tr>
<td>VT Ratio</td>
</tr>
<tr>
<td>CT Ratio</td>
</tr>
<tr>
<td>Zone 1 Reach</td>
</tr>
<tr>
<td>Zone 2 Reach</td>
</tr>
<tr>
<td>Zone 3 Reach</td>
</tr>
</tbody>
</table>

Line parameters were given in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Line parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Length</td>
</tr>
<tr>
<td>Line Impedance</td>
</tr>
<tr>
<td>Line Angle</td>
</tr>
</tbody>
</table>

A a-to-ground fault was injected into system at 20km, 25km, 30km, 38km, 40km, 45km, 49km, 50km, 70km, 100km, 110km, 120km and 122km respectively. Fault duration was 0.3s-0.9s. Relay response was shown in Figure 7.

Figure 7. Trip time responses

4. HVDC INTERCONNECTION

In order to investigate distance relay operations during 2003 North America blackout, the Hydro-Quebec HVDC link was simulated using MATLAB based on a HVDC demo in MATLAB [54]. The HVDC transmission system was introduced by ABB in [55, 56] as well as in [57-59]. The transmission system connects hydro power station in James Bay area and load centres in Montreal and Boston. Main data was shown in Table 3 [55].

<table>
<thead>
<tr>
<th>Table 3. Main data of Hydro-Quebec HVDC link [45]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning year</td>
</tr>
<tr>
<td>Power rating</td>
</tr>
<tr>
<td>No. of poles</td>
</tr>
<tr>
<td>AC voltage</td>
</tr>
<tr>
<td>DC voltage</td>
</tr>
<tr>
<td>Length of overhead DC line</td>
</tr>
</tbody>
</table>

Main reason for choosing HVDC: Long distance, asynchronous networks.
The steady-state of the HVDC voltage at rectifier side and the HVDC voltage under a-to-ground fault at inverter side was shown in Figure 8.

![Figure 8. HVDC voltage a) Steady-state HVDC voltage at rectifier side b) HVDC voltage under a-to-ground fault at inverter side](image)

5. SIMULATION OF 2003 NORTHEAST AMERICA BLACKOUT

The modelled power system in Figure 9 represents 2003 Northeast America blackout networks.

![Figure 9. Modeled Power System](image)

AC system 1 was 345kV 5600MVA equivalent power network, which represented East power networks. The system was performed by a 13.8kV, 5600MW synchronous generator and a 345kV, 4000MW load. AC system 2 was 345kV 10GVA equivalent power network which represented New England power network during the event. Ac system 3 was Quebec Hydro power stations, which is a 735kV, 7902MVA equivalent power network. The 6000MW load represents Western New York System. AC system 1 connects to load through two 100-km lines. Between AC 1 and load there were two generation units G1 and G2 connecting to transmission lines. G1 and G2 were performed by simplified synchronous machines with nominal power rated 3000MW. T1 and T2 were 13.8kv/345kv transformers. Relay 1 was set to protect 100km line 1. Relay 2 was set to protect 100km line 2. Relay 3 was set to protect 20km line. Relay 4 was set to protect 100km line 3. Relay 5 was set to protect 100km line 4. Details were shown in Tables 4 and 5 below.
Table 4. Line parameters [61, 62]

<table>
<thead>
<tr>
<th>Line</th>
<th>Line Impedance</th>
<th>Line Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>100km1</td>
<td>0.01915+j0.092</td>
<td>78°</td>
</tr>
<tr>
<td>100km2</td>
<td>0.01915+j0.092</td>
<td>78°</td>
</tr>
<tr>
<td>100km3</td>
<td>0.0766+j0.3679</td>
<td>78°</td>
</tr>
<tr>
<td>100km4</td>
<td>0.0208+j0.3387</td>
<td>86°</td>
</tr>
<tr>
<td>20km</td>
<td>0.0766+j0.3679</td>
<td>78°</td>
</tr>
</tbody>
</table>

Table 5. Relay Settings

<table>
<thead>
<tr>
<th>Relay</th>
<th>Zone1</th>
<th>Zone2</th>
<th>Zone3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>80km</td>
<td></td>
<td>300km</td>
</tr>
<tr>
<td>R2</td>
<td>80km</td>
<td></td>
<td>300km</td>
</tr>
<tr>
<td>R3</td>
<td>16km</td>
<td>24km</td>
<td>120km</td>
</tr>
<tr>
<td>R4</td>
<td>80km</td>
<td>120km</td>
<td>300km</td>
</tr>
<tr>
<td>R5</td>
<td>80km</td>
<td>120km</td>
<td>430km</td>
</tr>
</tbody>
</table>

For comparison, a similar power network was modelled as well. The comparison network was set the same with modelled 2003 blackout system but interconnected by 230km HVAC transmission line. The network was shown in Figure 10. T3 was a 735kv/345kv, 1800MW transformer.

Figure 10. Comparison system

During 2003 Blackout, due to domino effect the first outage seen in Ohio finally affected New York system. At 1.2s, A-B-N fault was implied. Results were shown in Table 6.

Table 6. Simulation Results

<table>
<thead>
<tr>
<th>What happened during event</th>
<th>HVDC</th>
<th>HVAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 15:32:03 Hanna-Juniper 345-kV line tripped because of tree contact. The tripped line cause following lines overloaded.</td>
<td>At 1.2 Phase-to-phase-to-ground fault was implied into system. The 100km line 1 was tripped at 1.23s.</td>
<td>At 1.2 Phase-to-phase-to-ground fault was implied into system. The 100km line 1 was tripped at 1.24s.</td>
</tr>
<tr>
<td>16:09:06 East Lima-Fostoria Central 345-kV line tripped on Zone 3 relay.</td>
<td>At 2.27s 100km line 2 was tripped. Relay 2 Zone 3 A-B-N tripped at 2.27s.</td>
<td>At 2.71s 100km line 2 was tripped. Relay 2 Zone 3 A-N tripped at 1.71s.</td>
</tr>
<tr>
<td>During 16:09 to 16:10 several power plants tripped off the system.</td>
<td>At 2.27s 100km line 2 was tripped. Relay 2 Zone 3 A-B-N tripped at 2.27s.</td>
<td>At 2.3 G2 was tripped. Relay 3 Zone 3 A-B-N tripped at 2.3s.</td>
</tr>
<tr>
<td>New York-New England transmission lines disconnected at 16:10:46 due to apparent impedance.</td>
<td>At 3.35s 100km line 3 was tripped. Relay 4 Zone 3 A-N tripped at 3.35s.</td>
<td>The HVAC line was tripped at 2.91s. Relay 5 Zone 3 A-B-N tripped at 2.91s.</td>
</tr>
<tr>
<td>HVDC tie with Quebec remained connected to the western New York system.</td>
<td>The HVDC still connected to Load when other AC transmission lines tripped. Relay 5 did not trip.</td>
<td></td>
</tr>
</tbody>
</table>
As can be seen from results, after fault occurred, at 1.23s R1 tripped 100km line 1 which caused following 100km line 2 overloaded. R2 tripped line 2 at 2.27s due to Zone 3 protection. R3 tripped G2 at 2.81s after line 1 and 2 were tripped due to overloaded current. 100km line 3 was tripped by R4 due to apparent impedance. However, the HVDC transmission system remained transmitting power to load. R5 did not trip. Load was survived during blackout.

As a comparison, similar results were got from HVAC system. 100km line 1 was tripped at 1.24s after fault occurred. Then the following 100km line 2 tripped at 1.71s due to R2 zone 3 protection. G2 and 100km line 3 were tripped at 2.3s and 2.24s respectively. Unfortunately the HVAC line was tripped at 2.91s due to R5 zone 3 protection. The load lost power completely during blackout.

6. CONCLUSION
In order to investigate the impact of HVDC links constraining voltage collapse propagating through the networks, the 2003 Northeast U.S.A and Canada blackout was simulated using MATLAB. The modelled system was compared to a similar system where they were connected using a HVAC line. The two systems were operated under the same situation including fault type and fault position. The performance of a distance protection on the near end line was examined using MATLAB. The results demonstrate how a HVDC interconnection can constrain system collapse propagating through a transmission system. Results also suggest that using HVDC interconnection is better than HVAC interconnection since HVDC can help to enhance power system stability during system collapse.

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The Impact of HVDC Links on Transmission System Collapse (Hualei Wang)

BIOGRAPHY OF AUTHOR

Dr. Hualei Wang received his Ph.D. Degree from University of Bath, UK in 2015. His research interests include HVDC and distance protection. Currently he is working in State Grid Qingdao Electricity Supply Company in the Department of Distribution networks and automatic.


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