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Economic Assessment of HVDC Grids

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SUMMARY

There is a growing interest in applications of HVDC grids in many parts of the world. Comparing with individual HVDC links, HVDC grids can provide flexible energy transfers among multiple converter stations, improved system reliability, and reduced investment cost, etc. In particular, an offshore HVDC grid will allow the aggregation and delivery of power from offshore wind farms in different regions, resulting in lower variability and higher economic value for wind power.

Based on the latest research and developments, HVDC grids potentially offer many promising technical and economic benefits. However, it still requires some major technology breakthroughs to make HVDC grid functional, for example, flexible control, fault detection and protection, and components, such as DC/DC converter, etc. One such challenge is the economic and reliability criteria for planning and designing future HVDC grids in order to determine the optimal size of converters and evaluate alternative configurations of DC networks. It is essential to develop a tool that can simulate the HVDC grid operation in a competitive energy market environment and quantify its economic benefits of the integrated AC/DC power system.

This paper demonstrated the economic assessment of HVDC grids using the industry recognized software program GridView™ equipped with the recently implemented HVDC grid model. HVDC grids were flexibly modelled as DC buses, DC lines, and converters. The converters could be scheduled and optimized in coordination with generating resources and loads on the AC networks subject to both AC and DC network constraints. Case studies are then presented based on the HVDC grid test system proposed by CIGRE working group B4-58. The study calculated the estimated economic benefits of HVDC grids over the benchmarking isolated HVDC connections with given offshore wind generation profiles and generation bid curves. It also demonstrated how the individual lines and converters are utilized under different assumptions. Lastly, the paper discusses security constrained schedules considering dc line outages.

KEYWORDS
HVDC, Multi-Terminal HVDC, HVDC grid, economic assessment, offshore wind integration, security constrained economic dispatch.

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1. Introduction of HVDC Grids

HVDC grids have been proposed in many parts of the world including Europe, North America, and China. HVDC systems have been used to integrate renewable resources and interconnections between asynchronous AC networks around the world. The growth in renewable power generation, especially offshore wind farm and remote desert solar farm requires massive new transmission network. The interconnections to existing matured AC power systems are limited by right-of-way permit for new transmission lines and strict standard for reliability and stability. As such, HVDC grids became viable technical solution to above problems. The expansion of point-to-point (PtP) HVDC links to HVDC grids would accommodate integration of large renewable resources, e.g. 10 GW off-shore wind with flexible and reliable operations. In particular, an offshore HVDC grid will allow the aggregation of power from offshore wind farms in different regions, resulting in power generation profiles of lower variability and greater economics of wind energy utilization.

HVDC grid, also called multi-terminal Direct Current transmission system (MTDC), is economically competitive and technically feasible [1]. Over twenty years of operational experience in the existing MTDC systems based on Line Commutated Converters (LCC) HVDC, such as HQ to ISO-NE Sandy Pond and Pacific DC intertie, and the recent development in power rating of voltage source converter (VSC), one can expect that a VSC-MTDC with a higher number of terminals has the potential to become a superior alternative to integrate and transport large renewable energy resources. The currently planned VSC-MTDC systems have radial connection or near radial connection with up to 3-4 terminals only. It cannot have loop or more complicated connections due to technology limitation. The envisioned HVDC grids have DC loops, DC/DC converter, and parallel DC lines to allow flexible delivery of renewable energy from off-shore wind or desert solar to different countries based on demand. For example, European Offshore Supergrid has been proposed to bring together the off-shore wind generation and HVDC transmission to provide a secure, sustainable and uninterrupted supply of electricity to European member states [2].

The recent advances in VSC-HVDC technology enables development of mesh DC networks [1, 3]. HVDC grids potentially offer many promising technical and economic benefits, including.

i. more efficient than the present AC grid on losses for longer distance transfers
ii. third of the size of AC systems for the same load
iii. link the asynchronized AC grids with different frequency
iv. integrate renewable resources over a broad range which could smooth out intermittency
v. flexible control of HVDC grid allows by-passing the congestion in AC systems
vi. enable reserve sharing among regions / nations to lower operating reserve
vii. facilitate electricity market beyond the boundaries and at affordable price
viii. provide voltage support to AC systems

However, the concept of envisioned HVDC grids is still under active development and a number of challenges remain to be solved. One such challenge is the economic and reliability criteria for planning and designing future HVDC grids in order to determine the optimal size of converters and evaluate alternative configurations of DC networks. It is essential to develop a tool that can simulate the HVDC grid operation in a competitive energy market environment and quantify its economic benefits of the integrated AC/DC power system.

The energy market simulation or power system production cost analysis programs currently can only model two-terminal HVDC systems. A multi-terminal HVDC system has been simplified as separate two-terminal systems. This simplification cannot accurately account for the effects of line and converter losses and the constraints in DC networks, and therefore will not be able to demonstrate HVDC grid's flexibility in control, reliability, and lowered losses for long distance bulk capacity transfer. To fully quantify the economic benefits of an HVDC grid, detailed model of DC networks (configuration and loss characteristics) is needed. The schedule of the converters should be optimized in coordination with generating resources and loads on the AC network subject to both AC and DC network constraints.

2. Model of HVDC Grids

HVDC Grid can be modelled in power flow programs and transient stability software such as PowerFactor and PSS/E, either using standard components available in the model library or through user defined models. These simulation programs can fully analyse the performance of HVDC grid under a single operating scenario with defined converter schedules. The schedule may not be optimal when generation costs and transmission congestion are not taken into consideration. Optimization of the converter controls for all the converters in HVDC Grids is essential to assess the full potential benefits of HVDC Grids. It requires a new tool to emulate the interactions among multiple controllable converters, linking between DC networks and AC systems. HVDC grid model has been recently implemented in the program to simulate the HVDC Grid operation and quantify its economic benefits to justify HVDC Grid projects. The program optimizes converter control to minimize the overall system production cost to meet loads and losses, subject to DC network constraints, AC networks constraints, and generating resource characteristics. It will help us to determine the size of each converter or line and compare the configuration of HVDC grids.

2.1 HVDC Grid Model Setup

GridView can import HVDC grid data in PSS/E format. In PSS/E, a HVDC grid can be represented as a multi-terminal DC (MTDC) line model which defines AC/DC converters, DC buses, and DC lines. The program also allows users to create a HVDC grid model through User Graphic Interface (GUI). DC lines connect between two DC buses with parameters like resistance, normal rating, and status. The converters connect between an AC bus and a DC bus with parameters like equivalent resistance, constant losses, rating, and status. The converters can be operated at rectifier mode (AC→ DC) or inverter mode (DC→AC) based on contracted schedule or dispatch optimization. Currently, DC/DC converter model is still under development. The data structure can model both monopole HVDC grids and bi-pole HVDC grids. For economic dispatch simulation studies, there is no difference between classical HVDC and VSC-HVDC grids except that different technologies may have different voltage, capacity, controllability, and loss characteristics. HVDC grids and AC systems are coupled by converters. Figure 1 shows the converter station modelling. A bi-pole converter station consists of two converters which interface the common AC bus with the bipole DC network with or without metallic return. A symmetric monopole converter station has only one converter which interfaces the AC bus with the monopole DC network.

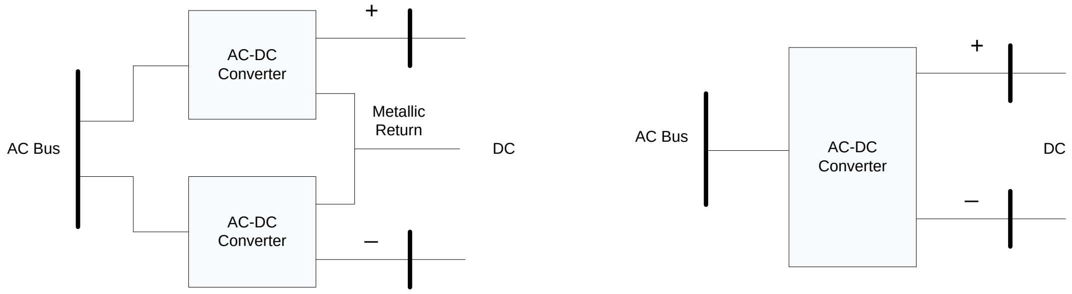


Figure 1. Converter station modelling: (a) bi-pole converter (b) monopole converter

2.2 DC Line and Converter Losses

In production cost simulation software, it is a common feature to model a 2-terminal HVDC line with losses. It is possible to mimic the flexible operation of a HVDC grid by multiple 2-terminal HVDC links between every pair of AC buses interfaced with the HVDC grid. However, the losses on the HVDC grid are significant different than the losses estimated in the multiple 2-terminal HVDC systems because losses are not superimposable due to nonlinearity. Losses are the primary consideration to determine converter dispatch when no congestion in both AC and DC networks. The optimal schedule for converter is the key to efficiently operate the integrated AC and DC networks. When either AC network or DC network overloaded, the dispatch of converters will mitigate violations first and maintain the desired power transfer levels in the integrated AC and DC system. Losses become the secondary issue for flow distribution between AC and DC networks.

The converter and line losses are the quadratic function of the converter and line flows. Converter also has constant no-load losses. The non-linear losses are the major challenge for the HVDC grid modelling. For modelling a two-terminal HVDC line, piece-wise linear function is typically used to model quadratic losses. It is much more difficult to represent losses in the same way for a DC grid due to meshed networks. The implemented losses model has been verified with power flow program. The test showed that the calculated losses in a HVDC grid testing system using the program have less than 3% standard error, comparing with the losses calculated from PowerFactor. Due to the volatile nature of the generation from offshore wind farms, the flows on DC networks and converters are changing frequently on the magnitudes and directions. Thus, the loss model must able to follow the power injection and network flows closely to ensure the accuracy under various operating conditions.

2.3 Integrated AC/DC Economic Dispatch

Conventional generating resources and loads are connected to AC systems while DC grids mainly connect remote renewable resources to load centers and interconnect regional AC systems to by-pass the congested bottlenecks. AC/DC converters are the interface between AC systems and DC systems, and each AC/DC converter has AC injection to AC system and DC injection to DC system. AC injection will contribute to AC network flow and loss calculation. DC injection will participate in DC network flow and loss calculation. If AC/DC converter is operating as a rectifier, AC injection will be greater than DC injection by converter losses. If the converter is operating as an inverter, DC injection will be greater than AC injection by converter losses. Marginal losses were used to penalize the cost of generation and calculate AC system losses. The converter schedule will coordinate with thermal/hydro generation dispatch, variable renewable generation, and AC/DC networks congestions to achieve the best utilization of the diversified resources. Converter dispatch will impact both AC and DC network flow distribution. Therefore, it impacts on transmission losses and congestions in the integrated AC and DC systems. Thus, the integrated AC/DC economic dispatch means coordinating all the converters' setting points to minimize the system production cost to serve loads and losses, including both AC and DC system losses, subject to both AC and DC transmission constraints plus converter rating limits.

2.4 Uncertainty Models and Security Constraints

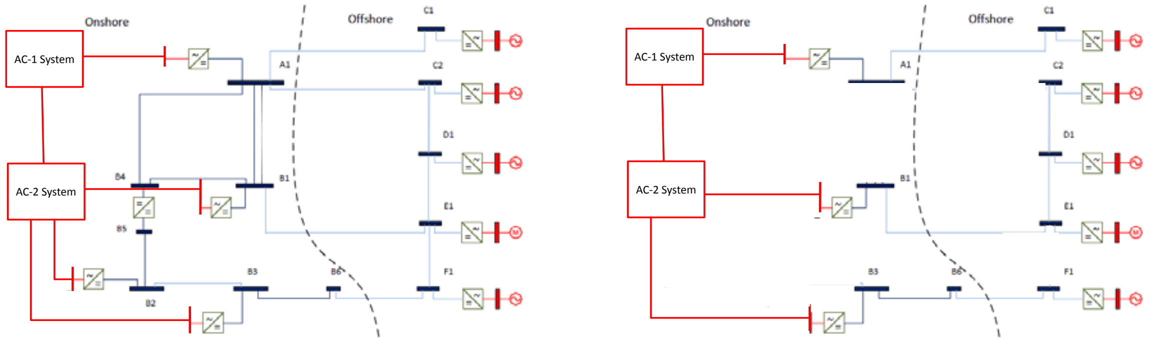
It is envisioned that a centralized HVDC grid control might need to handle operation of HVDC grid during real-time operation, especially during post-contingency. After any converter or DC line outage, the HVDC grid can reschedule the converters very fast to minimize the impacts on integrated AC/DC power systems. The outage events can be defined as planned maintenance or forced outages for DC lines or converters. Monte Carlo simulation has been implemented to emulate DC lines and converters forced outages, defined by forced outage rates and average outage duration hours.

AC system operation security requires that the line flow is not only below its normal rating under normal conditions but also below its emergency rating under contingency conditions of AC systems. Similarly, DC system operation security requires that DC line flow is not only below its normal rating under normal conditions but also below its emergency rating under contingency conditions of DC systems. As a DC line outage occurs, the other DC line flows may change accordingly even converter schedules do not change. If any violation in the DC line flows under contingency occurs, the converters' schedules will be adjusted to remove the violation under the contingency. Security constrained converter scheduling will make sure DC line normal and emergency ratings are met under normal and pre-defined contingencies, respectively.

3. Test System and Assumptions

3.1 HVDC Grid Test System

The HVDC grid test system proposed by CIGRE working group B4-58 is used to demonstrate the economic assessment of DC grids [4]. The single line diagram of the test system is shown in Figure 2(a), where we have extended two regional AC systems with load and thermal generation. AC-1 system is connected to the converter station A1; while AC-2 system is connected to the converter stations B1, B2 and B3. The two AC systems are linked by a tie line with limit of 1200 MW.



(a) HVDC grid

(b) Separate HVDC systems

Figure 2. Single-line diagram of the test systems

The HVDC grid test system consists of twelve DC buses, fifteen DC branches, nine AC/DC converter stations and one DC/DC converter. The offshore part of the DC grid has five AC/DC converter stations connecting four offshore energy sources and one oil/gas platform. We assume all the four offshore energy sources are wind farms. The onshore part of the HVDC grid has four AC/DC converter stations interfacing with the two regional AC systems. The HVDC grid test system is featured with three coupled loops thus allowing for flexible power delivery from the offshore wind farms to the AC systems, and adequate power transfer between the two regional AC systems. Except for C1 to AC-1, any DC line outage will not lose the connection of remote resource to load. As multiple renewable resources are integrated through HVDC grid over a large footprint, the intermittency of the combined generation will significantly be mitigated. In addition, reserve can be shared through HVDC grids. Therefore, the reserve requirements for the AC systems are reduced significantly. The reserve reduction benefits can be quantified but beyond the scope of this paper. The DC/DC converter is to help control the flow on DC branch B2-B5. Unfortunately, since the DC/DC converter model is not ready for the study, this DC/DC converter is replaced with a low impedance DC line in this paper. Detailed data of the HVDC grid test system are given in [4].

In order to demonstrate the economic benefits of HVDC grid over today's HVDC systems, we created a benchmarking system with three separated HVDC systems as shown in Figure 2(b). This benchmarking system was created by removing several DC branches, the DC/DC converter, and three DC buses (B2, B4, and B5) from the test system. The first HVDC system is a PtP link connecting wind farm C1 to AC-1 system. The second HVDC system is a multi-terminal HVDC system connecting C2, D1, and E1 to AC-2 system in radial connection. The third HVDC system is also a PtP link connecting wind farm F1 to AC-2 system.

3.2 Supply and Demand

The peak loads of AC-1 and AC-2 systems are 4530 and 6510MW respectively. Off-shore wind farm capacity is 500 MW at C1, C2, F1; and 1000 MW at D1. The load of oil/gas platform E1 is 100 MW.

Table 1. AC system thermal generation supply curves

Supply Curve of AC-1			Supply Curve of AC 2		
Block	Capacity (MW)	Production Cost (€/MWh)	Block	Capacity (MW)	Production Cost (€/MWh)
1	500	25	1	500	25
2	500	35	2	500	50
3	1000	40	3	1000	60
4	1000	45	4	1000	70
5	1000	50	5	1000	75
6	1000	55	6	1000	80
7	1000	60	7	1000	85

Table 1 shows AC system thermal generation supply curves, each of them is defined by seven bidding blocks with total capacity of 6000 MW.

3.3 Study Cases

In this study, we will simulate three cases defined as follows. The first case (Case 0) is the base case of this study which follows the assumptions described in section 3.1 and 3.2. With the given supply and demand assumptions, low cost generation in the AC-1 system will be delivered to the AC-2 AC system through parallel AC path and DC path, and the offshore wind generation will be mainly delivered to the AC-2 system. In order to demonstrate the economic benefits of HVDC grid, we defined two cases representing increased utilization of the HVDC grids. In the second case (Case 1), the AC tie-line transfer limit is reduced from 1200MW to 800MW, thus higher utilization of the HVDC grid is expected. In the third case (Case 2), the generation capacity of wind farms at C1, C2 and F1 is increased from 500MW to 1000MW. The load of AC-2 system is increased by 15% and the generation capacity of AC-1 system is increased by 3000MW, 1000MW each for blocks 3 through 5. These three cases can demonstrate how DC grids response to resources and loads changes.

4 Case Study Results

4.1 Base Case Results

Figure 3 shows the base case dispatch results of the onshore converters (A1, B1, B2 and B3). The results confirm that A1 is operating mainly at rectifier mode, while B1, B2 and B3 are operating at inverter mode. Wind generation from offshore wind farms are fed into the AC-2 system. The study confirmed that the offshore converters (C1, C2, D1 and F1) are dispatched as rectifiers following hourly power generation of wind farms.

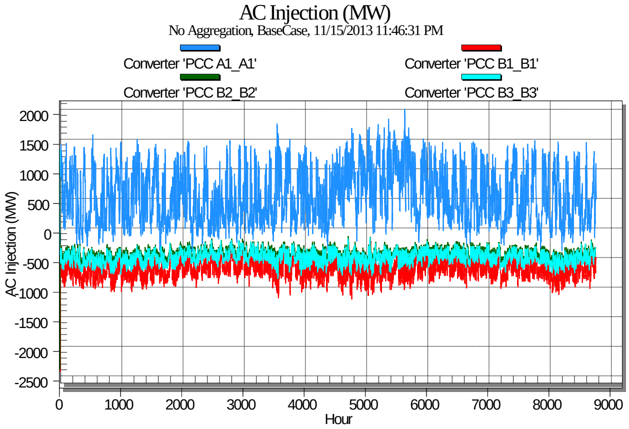


Figure 3. Dispatch results of onshore converters

Figure 4 shows the economic power transfer from the AC-1 system to the AC-2 system through parallel AC and DC paths. In principle, the power flow distribution between the AC path and the DC path is determined by integrated AC/DC optimal dispatch which minimizes overall system production cost to meet total load plus transmission losses. In the base case, there is no congestion on the DC path while the AC tie line is constrained for about 6000 hours.

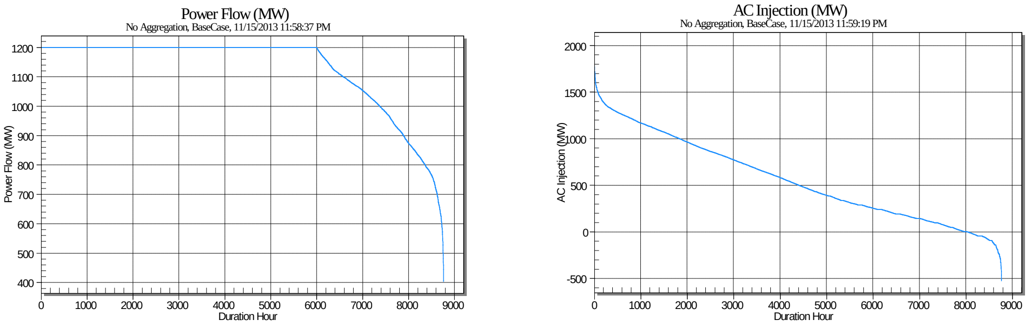


Figure 4. Power transfer from AC-1 to AC-2 in Case 0, AC path (left) and DC path (right)

4.2 Economic Benefits of HVDC Grid

Table 2 presents the calculated system average LMPs, generation production costs, and load payments for the three study cases (Case 0, Case 1 and Case 2) for the HVDC grid test system in Figure 2(a) and the benchmarking system with isolated HVDC systems in Figure 2(b), respectively. The simulation period is one year. The production cost savings and the load payment reductions (highlighted in bold) can be credited as part of the economic benefits for a HVDC grid. The study results clearly indicate that the economic benefit is highly dependent on the utilization of DC grid. Integrated AC/DC system production costing simulations are necessary to evaluate different HVDC grid designs from network topology to converter and DC line ratings.

Table 2. HVDC grid benefits under different scenarios

Case	HVDC Delivery Systems	Average LMP (€/MWh)	Total Generation (GWh)	Served Load (GWh)	Production Cost (M€)	Production Cost Reduction (M€)	Load Payment (M€)	Load Payment Reduction (M€)
0	HVDC Grid	53.96	54055	534289	1901	**57**	2936	**167**
0*	Isolated HVDC	52.51	53899	534289	1957		3102	
1	HVDC Grid	54.39	54148	534289	1906	**105**	2955	**227**
1*	Isolated HVDC	54.33	53812	534289	2011		3182	
2	HVDC Grid	47.80	59401	58274	1778	**336**	2845	**684**
2*	Isolated HVDC	49.21	58839	58274	2114		3529	

*: the benchmarking system with the same off-shore wind profiles and on-shore resources as DC grid testing system

Another important economic benefit of the HVDC grid shown in Figure 2(a) is that it not only provides a controllable DC path for economic power transfer from AC-1 system to AC-2 system, but also provides alternative path to deliver power from offshore wind farms to AC systems in case of contingency of any DC line (except A1-C1). However, in the benchmarking system, any contingency of connection cables may cause shut-down of one or more offshore wind farms.

Table 3 presents the calculated system average LMPs, generation production costs, and load payments for the base case (Case 0) considering cable outages for the HVDC grid test system in Figure 2(a) and the modified test system with isolated HVDC systems in Figure 2(b), respectively. In one set of runs, the connection cable B1-E1 was out-of-service for three months (April through June) and in another set of runs, the connection cable B6-F1 was out-of-service for the same three months. The study results clearly indicate that the economic benefits of a HVDC grid for keeping offshore wind farm operation under connection cable outages. No wind curtailment is in HVDC grid under cable outage while the benchmarking isolated HVDC systems have significant wind curtailments, 330 and 1220 GWh under B1-E1, B6-F1 outages, respectively. The production cost saving of DC grids increased by 126% or 33% under B1-E1 or B6-F1 cable outages, respectively, as shown in Table 3.

Table 3. HVDC grid benefits considering cable outages

Cable Outage	HVDC Delivery Systems	Total Generation (GWh)	Served Load (GWh)	Production Cost (M€)	Production Cost Saving (M€)	Load Payment (M€)	Load Payment Reduction (M€)	Wind Curtailment (GWh)
No	HVDC Grid	54,055	53,429	1,901	**57**	2,936	**167**	-
No	Isolated HVDC	53,899	53,429	1,957		3,102		-
B1-E1	HVDC Grid	54,057	53,429	1,901	**129**	2,936	**216**	-
B1-E1	Isolated HVDC	53,832	53,422	2,030		3,152		1,220
B6-F1	HVDC Grid	54,057	53,429	1,901	**76**	2,936	**177**	-
B6-F1	Isolated HVDC	53,886	53,429	1,977		3,113		330

4.3 Network Capacity Utilization

One of the benefits for DC grid simulation tool is to evaluate the design of DC networks and the size of converters. The design of DC grids is based on not only normal operating conditions but also contingency conditions. It may also have room to accommodate increased generating capacity and demand growth. Table 4 shows the maximum power flows of DC branches under normal operating conditions in the three simulated cases for the HVDC grid test system in Figure 2(a) and in the based case considering some selected DC line contingencies. The simulation results indicate that some of the DC branches, such as, A1-B1, A1-B4, A1-C1, B1-B4, and B2-B3 are lightly loaded under normal operating conditions and the selected contingency conditions. The flows do not hit the limits under any normal and selected contingency conditions. Based on assumed data in this paper, some part of DC grids can be downsized to reduce the investment cost if no major resource additions are expected in the futures. For example, double circuit A1-B1 can be reduced to single circuit. Additional studies may be required to fully exam all N-1 contingencies in DC grids.

Table 4. DC network power flows under normal and contingency conditions

				Normal Conditions			Contingency Conditions for Base Case			
From Bus	To Bus	CKT	Capacity (MW)	Base Case	Case 1	Case 2	B1 to E1 outage	B2 to B5 outage	B6 to F1 outage	D1 to E1 outage
A1	B1	1	2400	604	720	1,008	589	607	594	931
A1	B1	2	2400	604	720	1,008	589	607	594	931
A1	B4	1	2400	528	583	864	502	347	694	763
A1	C1	1	1812	495	495	991	495	495	495	495
A1	C2	1	1812	544	544	894	850	564	743	1,468
B1	B4	1	2400	144	147	197	160	347	815	71
B1	E1	1	1812	574	524	761		524	1,169	649
B2	B3	1	1812	217	217	326	432	720	781	145
B2	B5	1	2400	576	714	1,008	608		1,501	809
B3	B6	1	2400	935	1,035	1,419	1,105	1,501	0	730
B4	B5	1	2400	576	714	1,008	608	0	1,501	809
B6	F1	1	1812	938	1,038	1,426	1,105	1,501		730
C2	D1	1	1812	544	616	978	570	658	386	991
D1	E1	1	1812	1,196	1,297	1,623	1,018	1,331	991	
E1	F1	1	1812	797	901	1,234	917	1,355	495	548

4.4 Power Transfer on Parallel AC and DC Paths

One of advantages of DC Grids is to flexible control or by-pass the congested AC systems. Converters can be scheduled to minimize system production cost subject to AC and DC network constraints. Figure 5 and Figure 6 present the power transfer from the AC-1 system to the AC-2 system and the flow distribution between the AC path and the DC path under different assumptions. In Case 1, when the AC tie line limit reduced from 1200MW to 800 MW, the AC tie line is constrained almost all the time and more power is injected from the AC-1 system into the HVDC grid and then delivered to the AC-2 system. In Case 2, as more economic power in AC-1 system is available to transfer to the AC-2 system, the AC tie-line is constrained for almost all the hours even with 1200MW limit and more power is injected from the AC-1 system into the HVDC grid and then delivered to the AC-2 system. It can also be seen that the DC path (converter A1) is constrained for about 330 hours.

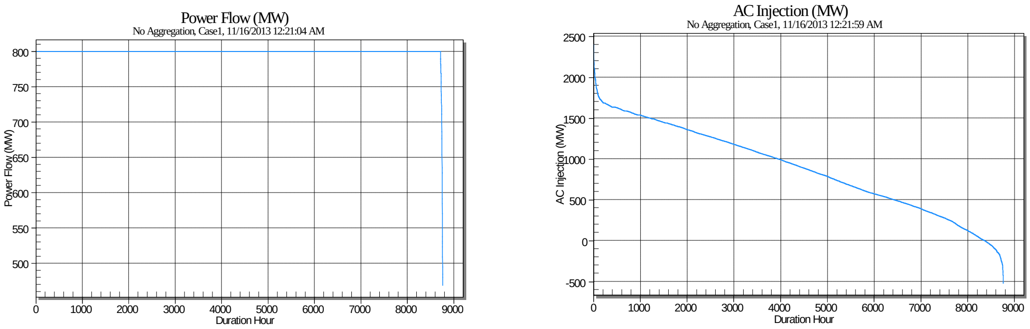


Figure 5. Power transfer distribution in Case 1, AC path (left) and DC path (right)

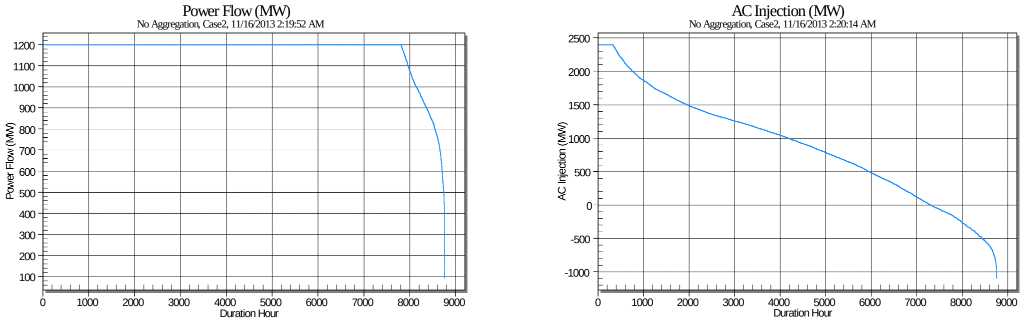


Figure 6. Power transfer distribution in Case 2, AC path (left) and DC path (right)

5. Conclusions

HVDC grids have shown many advantages to integrate large scale off-shore wind farms and remote solar farms into the existing matured AC systems. It not only improves operation flexibility and system reliability, but also mitigates aggregated intermittency and shares reserves among AC systems. It will bring significant economic benefits to consumers and renewable energy industry. To understand DC grids operation and economic benefits, HVDC grid model was developed in a commercial production cost simulation program. It mimics optimal HVDC grid operation to minimize the system production cost in the integrated AC/DC systems with losses.

The HVDC grid power flow and losses under different dispatch snapshots have been benchmarked with a power flow program. Illustrative case studies have been performed based on the HVDC grid test system proposed by CIGRE working group B4-58. The results of case studies have demonstrated the economic benefits of HVDC grids over the benchmarking isolated HVDC systems by providing reliable connection of offshore wind generation resources and high capacity DC path between regional AC systems.

Integrated AC/DC system production costing simulation programs are important tools for planning and designing future HVDC grids in order to determine the optimal size of converters and evaluate alternative configurations of DC networks. Further HVDC grid modelling features are currently under development including DC/DC converters. With these new modelling features, more advanced studies could be performed for the HVDC grids consisting of different voltage subsystems and power flow controllers [5].

BIBLIOGRAPHY

[1] CIGRE SC B4-52, “HVDC Grids Feasibility Study”, July 1, 2013.
[2] European Offshore Supergrid Proposal, Vision and Executive Summary. http://www.trec-uk.org.uk/resources/airtricity_supergrid_V1.4.pdf.
[3] J. Pan, R. Nuqui, K. Srivastava, T. Jonsson, P. Holmberg, Y-J Hafner, “AC Grid with Embedded VSC-HVDC for Secure and Efficient Power Delivery”, IEEE Energy 2030, Nov. 2008.
[4] Y. Yang, T. Langeland, J. Solvik and E. Stewart, “Reliability Analysis of HVDC Grid Combined with Power Flow Simulations”, Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Nov. 2012.
[5] CIGRE B4.58, 57, “The CIGRE B4 DC Grid Test System”, Electra, October, 2013.