Electric Utility Deregulation and Restructuring and Power Technologies (DRPT 2008)
Nannjing, china, April 6 - 9, 2008

Economic Assessment of HVDC Project in Deregulated Energy Markets

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***Abstract*-- High Voltage Direct Current (HVDC) transmission technology has become increasingly attractive to deregulated energy markets due to its salient characteristics in comparison with AC transmission. In particular, the precise, fast and flexible controllability of HVDC transmission power flow can greatly improve power grid reliability, utilization and efficiency. In the United States, transmission economic study is a mandatory part of transmission planning processes and energy market simulation programs are commonly used for asset utilization assessment, bottleneck identification, and benefit analysis for system expansions. To quantify the benefits of HVDC project in deregulated energy markets, the market simulation tools must be able to adequately represent HVDC operational characteristics, such as controllability and losses. In this paper, economic transmission planning study process involving HVDC project will be discussed.**

***Index Terms*--Economic Assessment, HVDC Transmission, Locational Marginal Price (LMP), Market Simulation, Transmission Planning.**

I. INTRODUCTION

In Order 890 issued in 2008 by Federal Energy Regulatory Commission (FERC) of United States, it requires that each transmission provider's planning process needs to meet the Commission's nine planning principles which are coordination, openness, transparency, information exchange, comparability, dispute resolution, regional coordination, economic planning studies, and cost allocation [1]. In terms of the last two items, transmission economic study is a mandatory part of transmission planning processes. The Order 890 also requires identifying the transmission bottleneck and the remedial plan to remove congestion in whole or partial.

HVDC transmission technology has become increasingly attractive to deregulated energy markets due to its salient characteristics in comparison with AC transmission. In recent years, HVDC technology has been considered as one feasible planning alternative in US to increase power grid delivery capability and remove identified network bottlenecks. A quite few HVDC transmission projects have been constructed or planned. Some of them are merchant transmission projects.

One challenge in economic transmission planning is to quantify the benefits of a transmission upgrade project. To accurately evaluate the economic impacts of a transmission upgrade project, energy market simulation tool with a detailed transmission representation is required. Specifically, as far as HVDC transmission project is concerned, the representation of DC link could affect the simulation results significantly.

This paper explores a market simulation based transmission planning process to evaluate the economic benefit of HVDC transmission project. Section II will discuss technical and economic advantages of HVDC transmission technology. In Section III, the HVDC applications in deregulated energy markets are presented. Section IV will discuss market based economic assessment of HVDC transmission project using market simulation tool. In Section V, the economic assessment of a real HVDC project in New York ISO (NYISO) is demonstrated. Section VI gives conclusions.

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II. HVDC TRANSMISSION TECHNOLOGY

HVDC transmission systems provide attractive and even unique features for bulk power systems, for example, long distance bulk power delivery, long submarine cable, voltage stabilization, asynchronous interconnections and other applications for special circumstances [2]. Figure 1 shows the HVDC transmission projects operated in North America. In general, the applications of HVDC technologies can be categorized as follows:

- Interconnection of asynchronous power grids
- Generation outlet from rich and cheap generation areas to load centers
- Interconnection for purposes of relieving transmission congestions, submarine cable, etc.

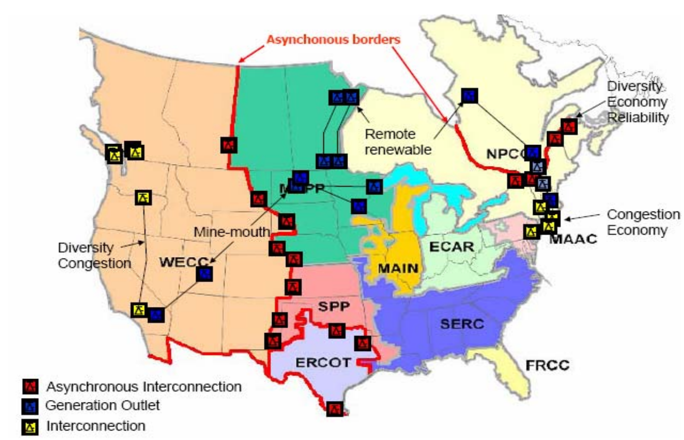

Fig. 1. Diverse applications of HVDC technology

A. Interconnection of Asynchronous Networks

Power import/export between two asynchronous AC networks can be easily implemented by HVDC back-to-back converters. As shown in Figure 1, multiple back-to-back HVDC links are installed along the border between Eastern Interconnection with Western Electricity Coordinating Council (WECC) and Electric Reliability Council of Texas (ERCOT). HVDC transmission technologies are also used to link asynchronous US, Canada and Mexico power systems.

B. Bulk Power Delivery through Long Distance

HVDC transmission systems are particularly suited and economic for delivering bulk power through long distance. In comparison to HVAC transmission, HVDC transmission consumes less conductor consumption, does not require intermediate substations and voltage compensation devices. As such, the annualized capital investment and operational cost of HVDC projects become lower than that of HVAC projects once the length of transmission system is longer than the so-called break-even distance. In addition, delivery of bulk power by HVDC transmission incurs less energy losses than through HVAC transmission. In recent years, a number of ±500kV HVDC transmission projects had been constructed in China to transmit bulk power from central and western hydro generation plants to the heavy load centers in the east coast region and the southern region. More HVDC transmission projects are planned and some of them already under construction including two ±500kV HVDC transmission projects.

C. Congestion Managements

HVDC transmission can bypass the congested pass and deliver power to the load center. Its deliverability will not be affected by the congestion of parallel AC systems as long as the receiving and sending ends have strong connection to AC systems. In some cases, AC line may not even be a feasible option due to the congestion of AC systems. Due to HVDC's controllability and no loop flow from system, it could be a better choice for a merchant transmission project.

D. HVDC Light

HVDC Light is a new technology to transmit power underground and under water over long distance [3]. Besides power exchange, HVDC Light transmission has a number of additional system operational advantages:

- Sharing of spinning reserve
- Emergency power import/export
- Dynamic voltage support
- Fast response to contingencies

It offers numerous environmental benefits, including "invisible" power lines, neutral electromagnetic fields, oil-free cables and compact converter stations. With extruded DC cables, power ratings from a few tens of megawatts up to more than thousand of megawatts are available. The converter station design is based on voltage source converters (VSCs) employing IGBT power semiconductors that operate with high frequency pulse width modulation. HVDC Light has the capability to rapidly control both active and reactive power independently of each other, to keep the voltage and frequency stable. One example project is the Cross-Sound Cable (CSC), a 39 km long submarine cable with 330 MW capacity buried in Long Island Sound that connects the electric transmission grids of ISO-New England and Long Island, NY in NYISO [4]. Another recent project is the Estlink Transmission System which operates at ±150 kV DC and is rated at 350 MW of active power in either direction. The link interconnects the national grids of Estonia and Finland, enabling the exchange of electric power between the Baltic states and the Nordel electric system.

III. HVDC Applications in Deregulated Energy Markets

A. Power Flow Controllability of HVDC

One of the most attractive features of HVDC transmission system is the precise, fast and flexible controllability of power flow at any desired level within the capacity limit. Transmitting the required current and power is implemented by controlling the converter valves, the core of the HVDC station, which is used for rectifying or inverting electric current. On the other hand, the power flow of AC transmission purely complies with Kirchhoff's laws and is based on the network topology and impedances. In the operation of deregulated energy markets, there are many concerns on lack of adequate power flow controllability and increased network congestion and so-called loop flow or parallel flow problems. Embedded HVDC transmission provides a feasible solution to mitigate these problems. The full controllability of HVDC transmission enables optimized power sharing between parallel AC lines and DC links and controlled inter-area or inter-market power exchanges. Fast flow controllability of HVDC transmission is also desirable for ensuing system security and contingency response.

B. HVDC Operation in Deregulated Energy Markets

In the energy market, the market players submit their bids for energy production or consumption to the ISO or RTO, who is responsible for scheduling the system resources for each hour of the following day (day-ahead market, DA) and the next hour (hour-ahead market, HA) to meet system load subject to transmission and security constraints. This optimization process is commonly called Security Constraint Unit Commitment (SCUC) and Security Constraint Economic Dispatch (SCED). As a fully controllable transmission device, the power flow of HVDC links can be optimally determined in Day Ahead market and Hour Ahead market scheduling based on system economics and security requirements. Therefore, ISO will benefit from HVDC transmission due to increased flexibility to schedule generation and effective congestion management. HVDC transmission system can also be operated as a merchant transmission facility. Similar to a merchant generator, a merchant HVDC transmission system requires a dispatcher to respect both contractual obligations and system security requirements. Flow controllability makes the settlement of pricing power transfers, billing customers, and preventing free riders become easy tasks. One example merchant transmission project in US is the Neptune HVDC

Project which connects PJM Regional Transmission Organization (RTO) and NYISO. The HVDC link allows Long Island of NYISO to access diverse sources of low-cost electrical capacity and energy from PJM market and the power flowing on the HVDC link bypasses the congested bottleneck of Long Island import. Furthermore, expensive and less efficient Reliability Must Run units are no longer needed.

IV. Market Based Economic Assessment of HVDC Transmission Planning

Transmission planning is a very complicated and comprehensive process which involves different kinds of required analysis of steady state, dynamic, stability, reliability and economics [5]. Economics assessment of a HVDC project in the competitive wholesale market is a relatively new task for ISO/RTO. A thorough economic evaluation of proposed HVDC projects versus alternative AC or other plans is required under the deregulated market environment. Accurately forecasting the impacts and benefits of a new HVDC project for all market participants requires a comprehensive market simulation tool that can handle detailed bulk power systems.

A. Economic Assessment Methodology

To evaluate the economic impact of a transmission project, it is necessary to quantify if the proposed project leads to more efficient economic dispatch, eliminate transmission bottlenecks and bring economic benefits to the consumers in the markets. Economic assessment will estimate production cost, generation revenue, congestion cost, load payment, and the cost allocation of the new project to appropriate parties. Each market, such as PJM, ISO-NE and CAISO, has established its own regional transmission expansion planning procedure that includes economic assessment. For instance, CAISO has developed Transmission Economic Assessment Methodology (TEAM) for its economic assessment [6].

ISO is not the only one who concerns about economics of a transmission project, the economic benefit of such project is also a key incentive for the Merchant Transmission Owner (MTO). The long-term benefit estimation of a HVDC project for MTO includes capital cost of line/cable, converts and right-of-way, and the revenue in terms of transmission tariff, maintenance, line usage and market price, discount rate, and so on. If the unknown items in planning stage, like line flow level and market price, can be accurately forecasted, it will give MTO better confidence and knowledge in making investment decision.

B. Market Simulation

To accurately quantify economic benefit of a transmission project, a market simulation program, which integrates transmission and generation planning in a deregulated energy market, is required [7]. Essentially, the core of the market simulation tool is an optimization engine to perform SCUC and SCED with considering detailed transmission and generation representations. The chronological simulation closely mimics the operation of energy market and determines LMP, generation and transmission utilization, system congestions, reliability indices and overall market performance. The typical structure of the market simulation tool is shown in Figure 2.

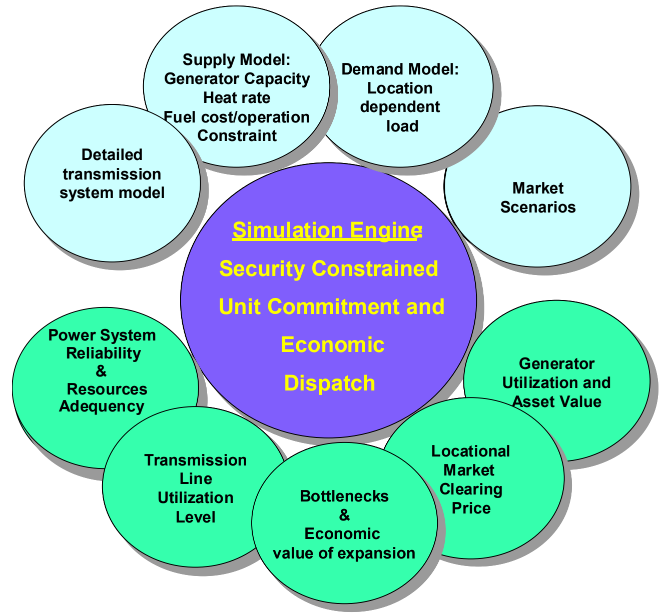

Fig. 2. The structure of integrated electric power system and market analysis

A good database of detailed transmission, generation and load in an energy market is the prerequisite of successful simulation. Data can be classified into the following broad categories:

- Supply – Generating units types, capacity, thermal unit heat rates, operational characteristics, bidding information, hydro generation, pumped storage plants, and renewable resource production data
- Demand – Spatial load distribution over time
- Transmission – Network topology, transmission line characteristics, and transmission constraints, such as, interface limits, operational nomograms, and contingency constraints

Besides the deterministic market conditions, economic analyses also have to address uncertainty of future market condition. Typically, the uncertainties include market rules, generation and transmission availability, hydro condition, fuel price, load forecast and bidding strategies. The tool not only quantifies the benefits for each market's entity but also is capable to calculate probability of the benefits.

C. HVDC Transmission Model for Market Simulation

Because of the flow controllability of HVDC, it is modeled completely different from AC lines. HVDC line flow can be scheduled based on either contractual agreement or market condition, such as LMP (Locational Marginal Pricing) price and transmission congestions. Conceptually, HVDC lines are modeled as a controllable device to incorporate with generation dispatch to meet system demand with respect to transmission constraints and minimizing system production cost. Meanwhile, the flow limit, operation and maintenance cost, wheeling charge and ramping rate (depends on the type of technologies) of HVDC lines need to be taken into consideration as well. Large system simulation capability is desired to capture the short-term transactions between energy markets. Especially, for the HVDC links connecting two markets, the HVDC flow should be scheduled based on both market conditions.

One of the three components of LMP is loss component that reflects the loss adjustment cost to serve the next MW load at specific network location, as well as the out-of-merit generation re-dispatch. Because transmission losses are the quadratic function of line flow, modeling losses in linear programming based market simulation tool is a challenge. Loss modeling for HVDC links is completely different from AC transmissions loss modeling and requires special treatment due to the controllability of DC line flow. HVDC flow will increase as the LMP at receiving end is higher than the LMP at sending end plus its operation cost and DC incremental cost of losses till the limit of the DC line is reached. Modeling HVDC system with and without losses may result in a quite different flow pattern and has significant impact on the economic assessment of the HVDC project. Figure 3 lists the flow duration curve of Pacific HVDC Intertie (PDCI) based on 2002 historical data and 2008 WECC study results with and without modeling loss. Modeling loss will give a more realistic flow pattern.

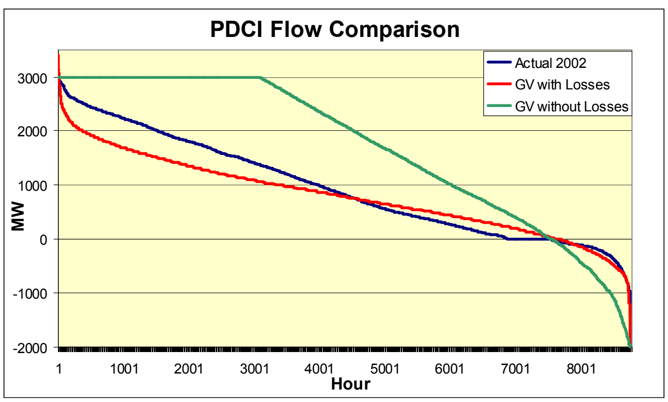

Fig. 3. Pacific HVDC Intertie flow comparison

V. Case Study

A. Background

As a study example, a market based economic assessment of a proposed New York Regional Interconnection (NYRI) HVDC project in New York ISO (NYISO) control area, has been performed using a market simulation program, GridView [8]. Figure 4 shows the NYRI HVDC project, extending 190 miles from upstate New York to southeast New York immediately close to New York City (NYC) [9]. The two terminals of NYRI HVDC are located in Hudson Valley zone and Mohawk Valley zone, respectively. It is designed with a rated power flow capacity of 1200MW at a nominal voltage of ±400kV. The study system database was built based on the NYISO system data available from public domains and is comparable to the real system in scope and complexity. However, no claim is being made by the authors that the projected system conditions and modeling assumptions are consistent with NYISO or MTO projections. The methodology and procedure in economic analysis and transmission planning study are shown below. The simulation results and analysis are presented here for illustrative purposes only.

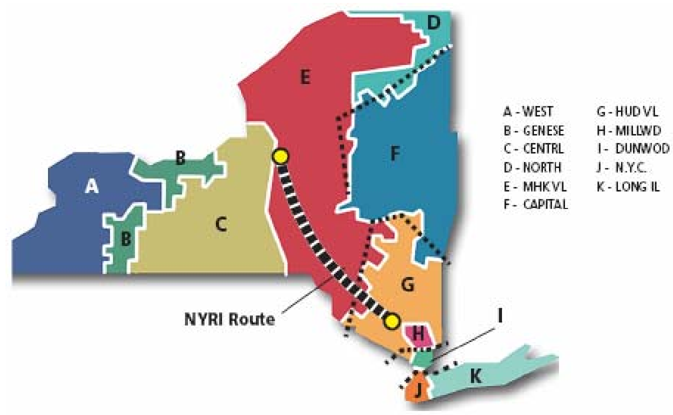

Fig. 4. The NYRI HVDC project layout in NYISO control area

Foremost, it is critical to establish a credible base case with existing systems [10]. In this study, besides NYISO control area, it is necessary to include immediate neighbor systems, PJM and ISO-NE, for accurately modeling the boundary flow condition and power exchange. There are about 2000 generation units (thermal, hydro, pumped storage, renewable resource) in the model. Detailed three-pool transmission systems from 0.48 kV to 765 kV are included in the database. Flow limits of major transmission branches, interfaces, and contingency constraints are enforced.

B. Simulation Results and Analysis

Two one-year simulations of the base case and the case with the HVDC project were performed. The base case was tuned and benchmarked against historical market data, such as, power flows of major interfaces, zonal hourly LMP values. Figure 5 illustrates the power flow benchmark for UPNY-CONED interface between historical data and simulated result.

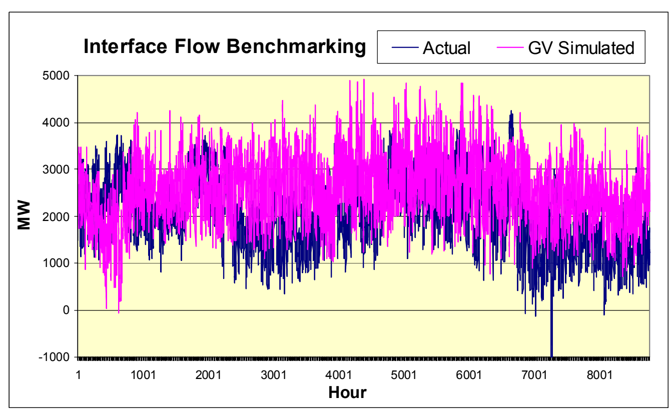

Fig. 5. Interface flow benchmarking for base case

Figure 6 shows the chorological and duration curves of the NYRI HVDC power flow during the simulation year. The HVDC is fully loaded for more than 1000 hours and operated above 700 MW for about 75% time of the year. Especially, during summer peak months, more power is delivered by the HVDC from north to southeast of NYISO bypassing the congested AC networks.

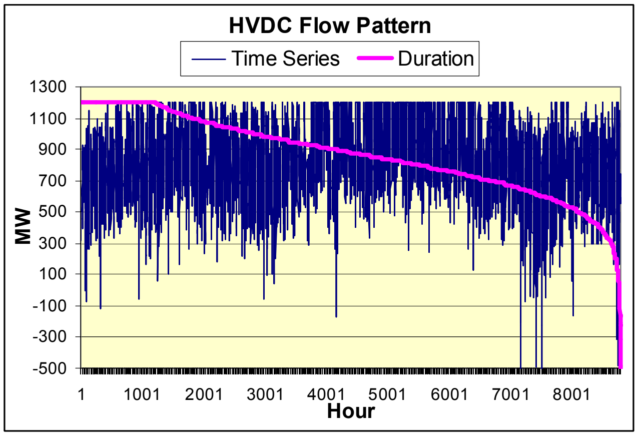

Fig. 6. The HVDC time series and duration curve

Table 1 shows the comparison of NYISO zonal load weighted LMP between the two cases. Cheap and clean energy was delivered from the north to congested downstate areas for most of the time. The results show that, with the NYRI HVDC link, the annual average LMP of all NY downstate zones, including Hudson Valley, Long Island, Millwood, NY City and Dunwoodie, consistently decreased about 0.5 $/MWh. On the opposite, LMP of the upstate NY zones increases. Furthermore, the LMP difference between Hudson Valley and Mohawk Valley zones reduced from 3.35 $/MWh to 1.94 $/MWh.

TABLE 1
NYISO ANNUAL AVERAGE ZONAL LOAD WEIGHTED LMP ($/MWH)

LMP ($/MWh)	Base Case	HVDC Case	Difference
Hudson Valley	52.28	51.77	-0.52
Long Island	53.95	53.52	-0.43
Millwood	52.76	52.25	-0.51
NYCity	52.92	52.45	-0.46
West	46.27	46.97	0.70
Dunwoodie	52.83	52.33	-0.50
Central	47.62	48.42	0.80
North	48.77	49.74	0.97
Mohawk Valley	48.93	49.83	0.90
Capital	50.75	51.21	0.46
Genessee	47.46	48.33	0.87

Table 2 presents the annual NYISO zonal load payment changes with NYRI project and one can see that zones in southeast NY pay less for the energy. Furthermore, for the most congested load centers, NY city and Long Island, load payment has been reduced the most. The main reason is because the HVDC link can transfer cheap power from upstate NY. Consequently, less energy is provided by the local expensive units. Additionally, NYISO, as a whole, benefits from the lower average LMP and less energy cost.

TABLE 2
NYISO ANNUAL ZONAL LOAD PAYMENT (M$)

Load Payment (M$)	Base Case	HVDC Case	Difference
Hudson Valley	601.63	594.52	-7.11
Long Island	1408.08	1393.06	-15.02
Millwood	151.29	149.43	-1.85
NYCity	3288.43	3251.16	-37.27
West	757.69	769.42	11.73
Dunwoodie	385.17	380.23	-4.94
Central	842.44	856.47	14.03
North	351.59	358.38	6.79
Mohawk Valley	371.14	378.05	6.91
Capital	590.11	596.50	6.39
Genessee	552.95	563.58	10.63

Transmission flow pattern and congestion bottleneck has been changed quite a bit due to the controllability of HVDC to avoid causing loop flow on parallel AC systems. The parallel AC system's congestion costs decrease due to NYRI project. For example, congestion hours of UPNY-SENY interface, mainly representing the power import to Hudson Valley from upstate NY (see Figure 4), decreases by 88%. The NYRI may increase the congestion cost of its downstream paths, especially for the originally congested paths into NY City. For example, average flow of Dunwoodie South interface, crossing NY City, Long Island and Dunwoodie, increases by 20%.

C. Economic Benefit Calculations

In quantifying total NYISO societal economic benefits of the NYRI HVDC project, its societal economic benefits consist of three parts: the reduction in consumer payments, the increase in generation net profit, and the increase in congestion revenue.

- Consumer Surplus (CS) – reduction in load payments
- Producer Surplus (PS) – profit of generator owners
- Transmission Surplus (TS) – increase in the transmission rent
- Total benefits = CS + PS + TS

Based on the described methodology, table 3 shows the annual economic benefit of the new HVDC link in NYISO during the simulation period. As expected, consumer payment is reduce 9.72 M$. However, producer net profit increases 27.45 M$. It indicates that building the HVDC link will bring more economic benefits for generation owners than load consumers. Total transmission congestion revenue decreased by 10.89 M$. Therefore, transmission owner will collect less congestion rents. Overall, the NYISO societal economic benefit from the new HVDC link is 26.28 M$ for the study year.

Based on the study result, the NYRI HVDC project will bring annual benefit of 26.28 M$. However, life cycle analysis will need to be performed to complete economic assessment. Ideally, if the southern terminal of HVDC can be extended into NY City, higher economic benefits and less transmission bottlenecks will be expected. Besides the economic and engineering concerns, nevertheless, the right-of-way and related policy of city infeed transmission expansion will also need to be addressed.

TABLE 3
NYISO ECONOMIC BENEFIT WITH HVDC

NYISO Annual (M$)	Base Case No HVDC	With HVDC	Benefit (M$)
Consumer Payment	9300.53	9290.81	9.72
Producer Net Profit	2573.81	2601.25	27.45
Congestion Cost	148.20	137.31	-10.89
Total NYISO Benefit			**26.28**

D. Benefit Analysis of AC Alternative

A simulation of HVAC alternative transmission upgrade was also performed in order to compare its benefit with the HVDC project's one. The new 345 kV AC line is sited at the exactly same location as NYRI HVDC link. In table 4, the AC transmission upgrade brings total economic benefit of 10.18 M$ to NYISO system that is less than 26.28 M$, the benefit of HVDC project, as shown in Table 3. HVDC option can provide additional benefits for voltage supports and contingency responses, which are not addressed in the paper. HVDC line bypasses the congested AC system to deliver more power to load center while AC alternative is not fully used due to the congestion from parallel AC systems.

TABLE 4
NYISO ECONOMIC BENEFIT WITH AC ALTERNATIVE

NYISO Annual (M$)	Base Case No HVDC	With AC	Benefit (M$)
Consumer Payment	9300.53	9298.99	1.54
Producer Net Profit	2573.81	2588.67	14.86
Congestion Cost	148.20	141.97	-6.22
Total NYISO Benefit			**10.18**

VI. CONCLUSION

With many attractive features, HVDC technology will be more widely considered as transmission expansion option in deregulated energy markets. Economic assessment of a transmission project is important for market operators - ISOs, as well as merchant transmission investors. Therefore, HVDC model in market simulation program must correctly represent HVDC controllability and incremental losses, respectively. It will improve the accuracy for economic assessment of HVDC projects. In addition to HVDC model, the market simulation program must have detailed model of transmission systems, generation bid curves, and transmission constraints (including contingencies, interfaces, and operational nomograms, etc.). The security constrained unit commitment and economic dispatch will mimic system operation under deregulated markets. The co-optimization of regulation, ancillary service and energy markets will further enhance the market operation. With above features of market simulation program, it will capture the benefits of HVDC project. The example of HVDC project's economic benefit study showed that market simulation tool with detailed transmission model and capability to capture all market's rules is critical for quantifying economic benefits of a transmission upgrade in the deregulated markets. Additionally, it is an important and powerful tool to support transmission network investment decision.

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VIII. BIOGRAPHIES

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