A Novel Solution for California's Energy Crisis: Wind Power Transmission from Energy Rich North Dakota to California through HVDC Lines

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Abstract

This paper first investigates feasibility of establishing a 7,000 MW power capacity wind farm, and the conversion of the total AC electrical power of 4,000 MW to the DC in a large converter station in Olga, North Dakota. Then it includes transmission of this bulk power to Northern California through a 1,700 miles, two bipolar $\pm$500 kV, 2,000A high voltage DC (HVDC) lines. The study assumes that there exists an average AC electrical power of 4,000 MW generated through two wind farms located in Olga, ND with 10,000 MW capacity. An existing wind capacity factor (CF) of 40%, which shows actual or predicted output as a % of installed capacity, is considered for this study. Two wind farms are considered to be established at Olga 3 and Olga 5 locations with average wind data available by North Dakota Department of Commerce - Division of Community Services. The commercially available North Dakota wind resource alone is estimated at over 1,000 TWh (billion kWh) per year. Dakotas wind energy potential is very stranded allover the land. Manitoba HVDC Research Center's PSCAD /EMTDC power system software is used for the system modeling and simulation studies of the proposed HVDC scheme. Overall, the researchers determined that it is feasible and economical to establish a total power capacity of 10,000 MW from two new wind farms including 5,000MW at Olga 3, and other 5,000MW at Olga 5 wind sites, both are located in the north east corner of North Dakota, and one large 4,000 MW AC to DC converter station in Olga 5, and to transfer this DC power to the Northern California by HVDC lines.

I. Introduction

California's reliance on electrical power imports is increasing gradually as the state currently imports about 11,000 MW of power from other states and Mexico. Only about 5,000MW of new capacity is projected to come on line in California by 2004 [1-2]. Coal fired power plants are now the largest single source of power supply for Los Angeles and other metropolitan areas in California. Natural gas supplies about 20% of the City of Los Angeles' energy demand, hydroelectricity accounts for 12%, nuclear 9%, and the remainder comes from purchased power through wind, biomass, solar and cogeneration. Since June 2000, California's electricity market has produced extremely high prices as a result of deregulation. The difficulties that have appeared are intrinsic to the design of the market where the demand plays a significant role in the energy price. It is evident that without considering additional power sources, particularly environmentally friendly renewable sources, supplementing energy needs with clean and renewable sources becomes imperative due to energy crises and gradually growing environmental consciousness [3-6].

This research project proposes an Earth- friendly solution for California's well-known energy crises by transmitting North Dakota's rich wind power resources through high voltage direct current (HVDC) power lines. The rich hydro power from Oregon and Canada has already been transmitted to California through a 3,000 MW DC transmission line scheme called Pacific DC Intertie (PDCI), although this is still not enough due to the dramatically growing industrial power demand particularly in Northern California.

Due to the environmental impact of the "greenhouse effect," water and air pollution, and mining operations in ecologically sensitive zones, the generation of electrical power by Earth-friendly "green" technologies is of great current importance in engineering and technology research. The Upper Great Plains is known as the "Saudi Arabia of Windpower" of the United States [5-6]. According to the Department of Energy (DOE), North Dakota could supply 36% of the 1990 electricity consumption for the entire USA through wind power generation. However a very small percentage of the wind power resource is captured in North Dakota [5-9]. Another Midwest state, Iowa has become the third largest wind power producer after California and Minnesota. Wind power technology has become one of the fastest growing technologies in the world, and has constituted one of the most efficient green power technologies [10-13]. However, the Great Plains wind resources are almost totally "stranded", for lack of transmission systems by which to collect and export the energy.

II. DC versus AC Power Transmission

Some of the most significant properties of DC power transmission are (1) using only two wires as a positive and negative "bipole" compared with three separate lines in AC, (2) no frequency related stability problems occur in DC transmission since line reactance is not a function of frequency as opposed to the line reactance of AC transmission, (3) feasibility of power transmission in DC through extra-long distances of more then 1,000 miles whereas AC is limited to 350 miles for stable operation [14-16]. Commercial availability of HVDC schemes in the world has increased steadily during the last 35 years due to the development of high power and low cost power electronic devices together with the development of DC measurement and protection devices.

The role of HVDC transmission is also growing in the United States as a result of the following [17]: (1) because of very long distances between some of the power plants and the loads, AC power transmission has difficulties associated with higher transmission line inductances and associated stability problems; (2) due to the rising prices of imported oil and clean air restrictions on high sulfur eastern coal, high quality western coal, hydro resources, and now eco-friendly wind power are becoming more attractive to many electric power utilities. Since many of the major coal, hydro, and wind resources are in very remote locations, a conventional AC transmission system cannot operate in a stable fashion in these extra long distance applications; and (3) the increasing restrictions due to environmental concerns require the location of new power generating sites and transmission corridors away from both densely populated urban areas and environmentally sensitive areas like national parks.

Today, long distance overhead , underwater or underground transmission, and back to back ties between power systems having different ratings are some of the HVDC applications used effectively worldwide. Two of the advantageous of HVDC transmission are having only two conductors, and freedom from the skin effect. The DC line therefore has a smaller right of way (ROW) for the same power level compared with AC line as shown in Figure 1.

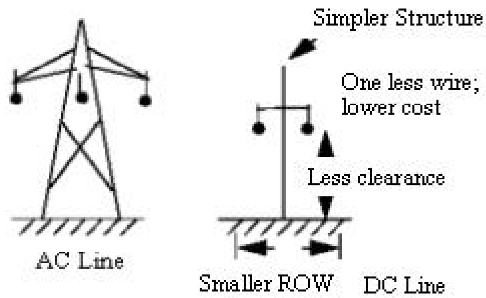

Figure 1. AC and DC Transmission Towers

It has been proven that HVDC power transmission is more economical than three-phase AC transmission for sufficiently long distances and higher power ratings. The economic advantage in this case is due to the lower cost of the lines. Therefore, electrical power generation through large wind farms located around remote locations, and then transporting electrical power to the densely populated load centers by long distance HVDC lines without stability problems, is economically more attractive than transporting particularly coal or oil by railroad or truck over long distances.

III. Proposed Project

The objectives of this research proposal for a novel solution for California's energy crisis are listed as follows: (1) Feasibility analysis of establishing a 10,000 MW capacity wind farm in Olga, North Dakota where the state's richest wind power resources exist as shown in Figure 2, (2) feasibility analysis of establishing a rated value of 4,000 MW converter station in Olga, ND to rectify the AC power to the DC. This 4,000 MW power is generated through 10,000 MW wind farm with a wind capacity factor of 40% in the region, (3) transmission of 4,000 MW DC power from Olga, ND to Sacramento, California, where a DC to AC inverter station will be built, through two parallel, 1,700 mile long, $\pm$500 kV, HVDC transmission circuits which may be co-located on a single set of towers, (4)modeling and simulation of the dynamics of the entire power system as shown in Figure 9 by PSCAD/ EMTDC [18], a well-known Electromagnetic Transients Program developed by Manitoba HVDC Research Center.

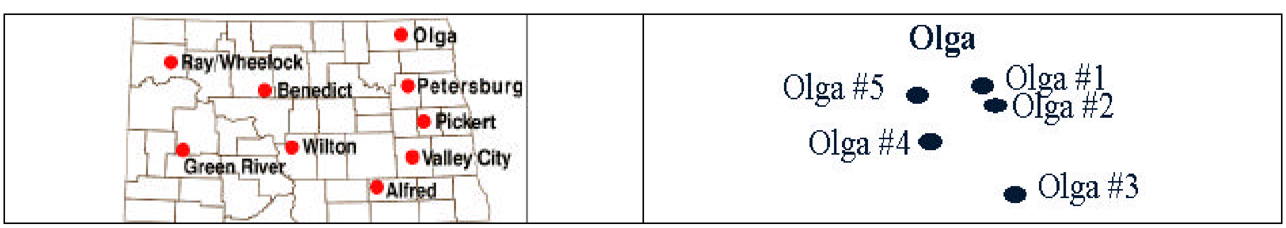

Figure 2. North Dakota's major wind sites and the proposed wind farm locations Olga 3 and Olga 5 [19].

The two wind farm locations and overall HVDC transmission line route are shown in Figure 3. Figures 4 through 8 compare daily wind speed changes for a specific time periods at Olga 3 and Olga 5 locations. It is interesting to observe wind CF effect during the indicated time intervals. For example, Figure 5 shows a wind speed value of 2.0 m/s determined from Olga 3 area at about 3:00 am while that of 6.0 m/s was measured from Olga 5 at the same time.

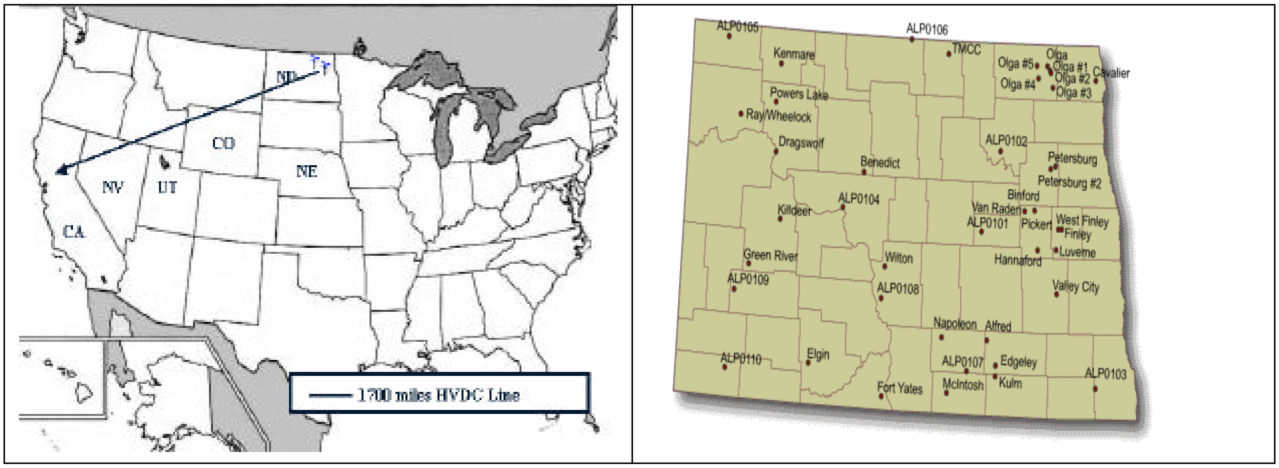

Figure 3. The proposed two new wind farms in Olga 3 and Olga 5 locations [19] in North Dakota and detailed wind locations.

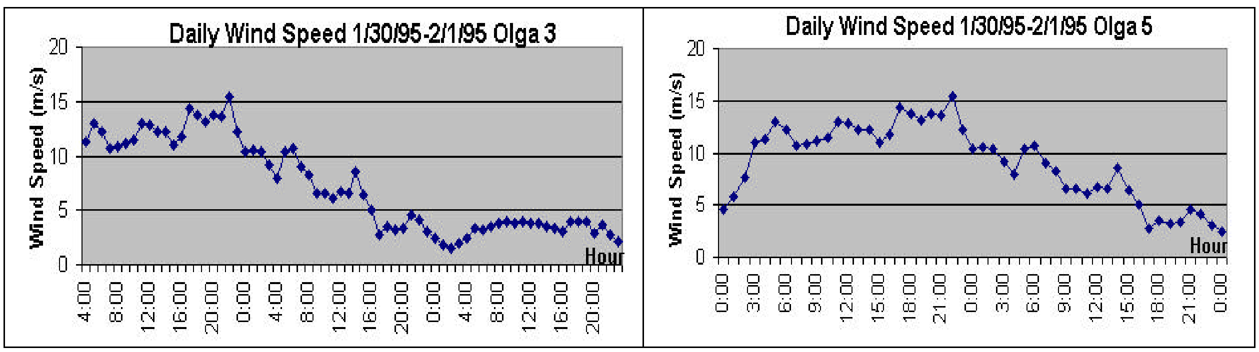

Figure 4. Comparison of Olga 3 and Olga 5 wind sites data for January 30-Febraury 1, 1995.

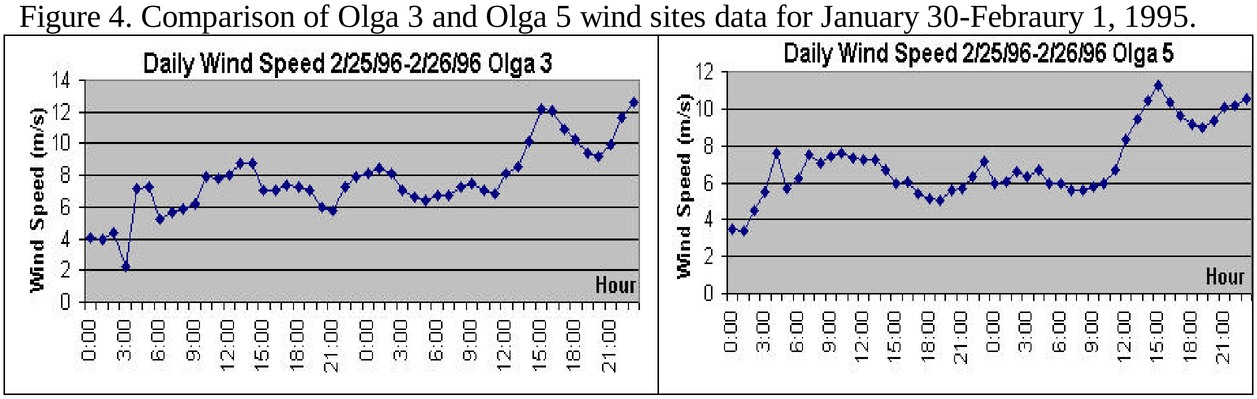

Figure 5. Comparison of Olga 3 and Olga 5 wind sites data for February 25-26, 1995.

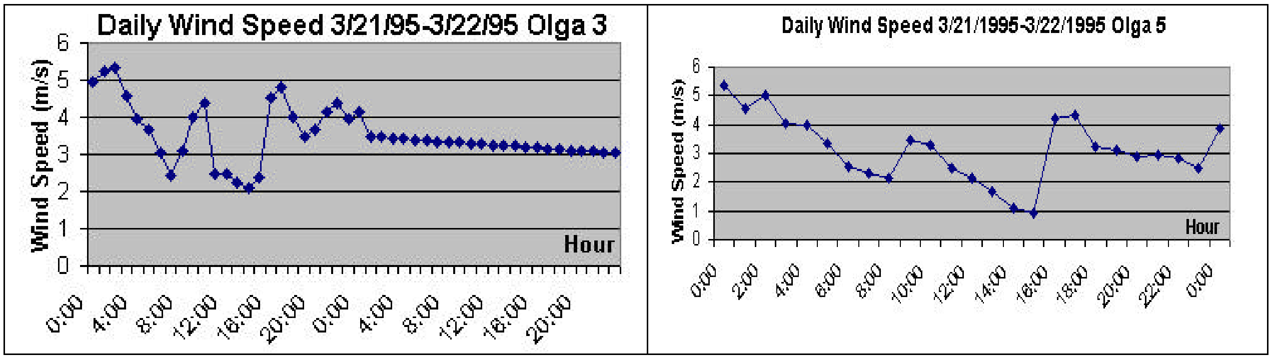

Figure 6. Comparison of Olga 3 and Olga 5 wind sites data for March 21 - 22, 1995.

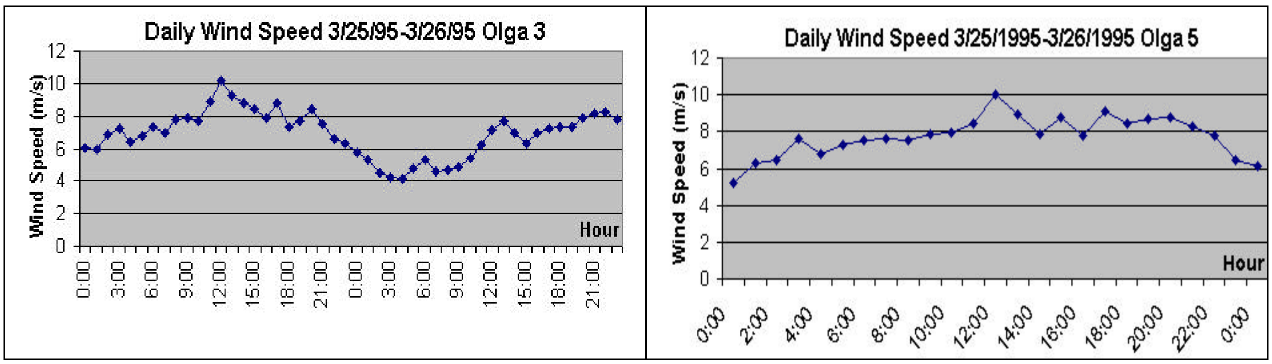

Figure 7. Comparison of Olga 3 and Olga 5 wind sites data for March 25-26, 1995.

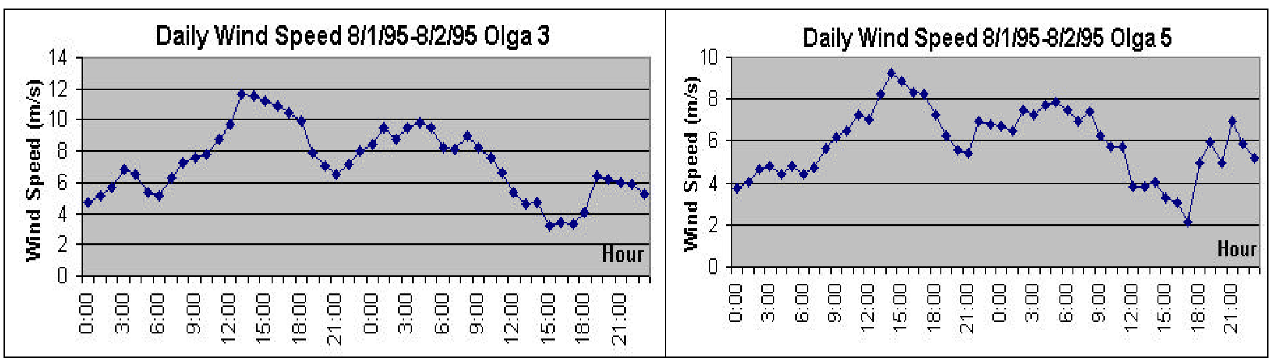

Figure 8. Comparison of Olga 3 and Olga 5 wind sites data for August 1-2, 1995.

IV. Wind Power Development in Midwest

Wind power is one of the potential renewable energy sources, which can be harnessed, in a commercial scale for many end users. The power available in a wind stream is proportional to the cube of its speed, which means that doubling the wind speed increases the available power output by a factor of eight as shown in Equation 1. Therefore, since the energy content of the wind varies with the third power of the wind speed, the economics of wind energy depends heavily on how windy the site is. Furthermore, the wind resource varies with the time of day, season, height above ground, and type of terrain.

$$P = 0.5 r A\, C_p v^3 h_g\, h_b \qquad \text{(Eq. 1)}$$

where, P in Watts , r = air density (about 1.225 kg/m^3 at sea level, less higher up), A = rotor swept area exposed to the wind (m^2), Cp = Coefficient of performance (.59 {Betz limit} is the maximum theoretically possible, .35 for a good design), v = wind speed in m/s, h_g = generator and, h_b = gearbox/bearings efficiency. The basis of a installing a successful wind energy facility or wind farm is to find a site which has a strong and steady wind. The more wind turbines on the grid, the more short-term fluctuations from one turbine may reduce the fluctuations of others. A large area of two windy locations called Olga 3 and Olga 5 in North Dakota may have an a positive impact on wind power generation by reducing possible wind power fluctuations. In fact, Figure 4 shows that Olga 3 and Olga 5 wind sites may be in complement of each others during the time of January 30 through February 1, 1995.

According to American Wind Energy Association, Olga in North Dakota has more than 600 W/m^2 of power class and an average wind speed of 8.0 m/s [5, 9, 13]. Wind power generation in North Dakota, and power transmission through HVDC lines is a clean, available, and cost effective alternative source of energy and, better yet, can be readily integrated with existing and new power grids. Therefore, it should be considered as a solution to California's energy crisis. The proposed project may bring thousands of new technical and managerial jobs mostly to North Dakota, California, and other states where the HVDC line is to be established.

V. Modeling and Simulation Study

Feasibility analysis of establishing new wind power plants called "wind farms" requires significant study. The main problem in grid connected wind farms is dynamics mismatch between the wind generators and conventional large size power generators in coal fired and hydro power plants. The harmonics injected from the converter and inverter stations in the HVDC schemes into the power grid also adversely affect overall system operation although DC filters mostly may solve these problems. Power transmission systems involving AC and DC lines have very complex interactions. Faults on the AC line can manifest themselves as power quality problems on the DC line and vice versa. The interactions include AC line problems generated by commutation failures in the converter stations due to DC line disturbances, and AC line voltage stability problems due to the wind generators.

The AC/DC interactions affect the overall performance of the proposed wind power transfer system [20-24]. Therefore, they must be investigated for reliable operation. The overall control scheme is based on a simple modulation controller keeping the DC power transfer constant by monitoring and controlling DC voltage, DC current, and firing angles of thyristors in both converter and inverter stations. PI or PID parameters can be determined optimally in PSCAD/EMTDC.

Achieving the most appropriate power system model including the generator excitation system, AC/DC lines, rectifier and inverter control systems are the key issues to address in trying to solve the problem.

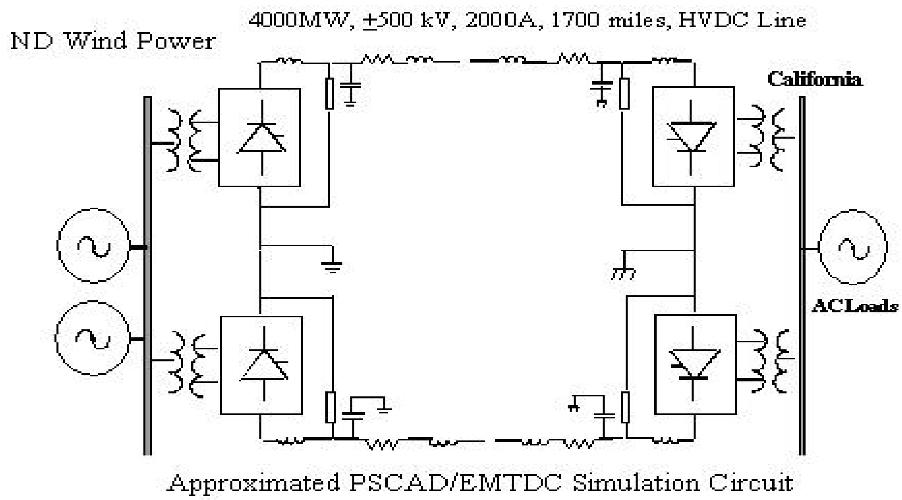

Figure 9. Proposed Bipolar HVDC System.

The overall system mathematical model has a nonlinear model shown as:

$$\dot{X}(t) = F(X(t), U(t)) \quad \text{(Eq. 2)}$$

where $\dot{X}(t)$ is first derivative of system state vector, and X(t) is system state variables including voltage, current, firing angle, power, and U(t) is control function for converter/ inverter stations.

Figure 10 depicts a functional block diagram of proposed 4,000 MW, ±500 kV, 2,000A, 1,700 miles, two bipolar HVDC system for wind power generation and transmission. The following five contingency cases are modeled and simulated by PSCAD/ EMTDC software for the overall AC/DC system performance: Case 1- A positive pole-to ground fault on the DC line at the North Dakota end, Case 2- A converter failure by temporarily blocking the firing pulses of one of the thyristors at the North Dakota rectifier station, Case 3- A positive pole-to ground fault on the DC line at the CA end, Case 3- A double pole fault on the DC line at the North Dakota end, and Case 4- A single -phase to ground fault on the AC line at the Olga end. Standard data library in PSCAD/EMTDC for HVDC line models, and converter stations are used for modeling purposes. The HVDC network also includes dc filter circuits since the converter and inverter stations generate a number of harmonics.

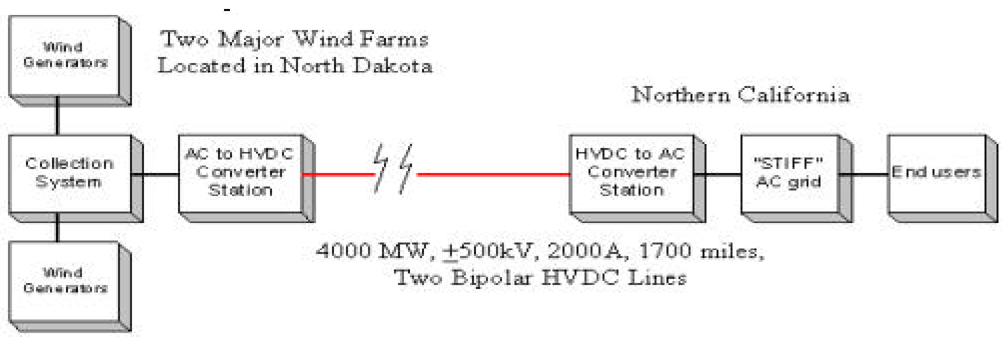

Figure 10. A functional block diagram of proposed 4,000 MW, ±500 kV, 2,000A, 1,700 miles, Two Bipolar HVDC System.

Figure 11 indicates simulation results of AC current waveforms, DC voltage across the HVDC line, and DC power transfer, while Figure also shows sending and receiving end DC power transmission waveforms when a single-phase to ground short circuit occurred at 0.3 s and cleared at 0.4 s in the North Dakota end.

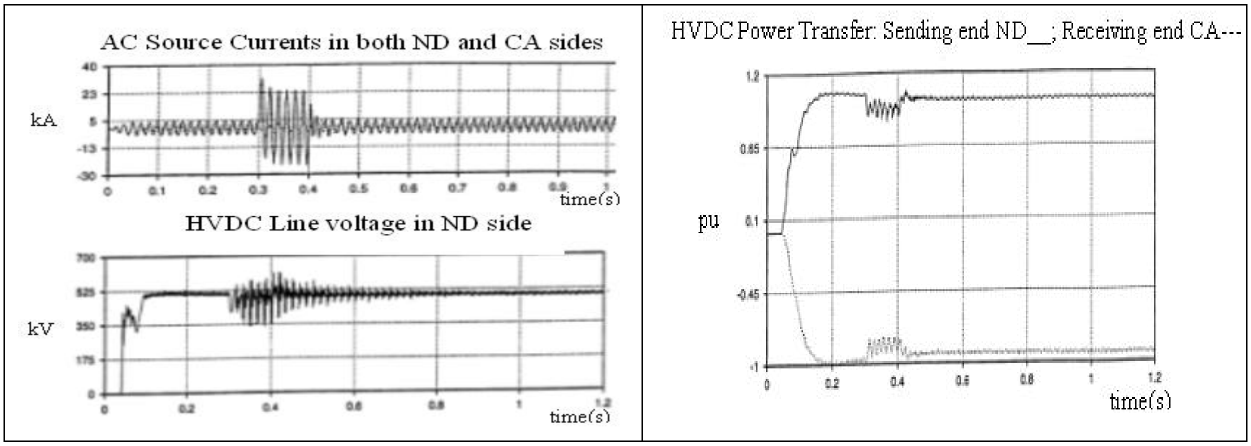

Figure 11. AC current waveforms in both ND and CA sides and DC line voltage during the fault and sending and receiving end DC power waveforms

VI. Cost Analysis

In this study 10,000 MW of wind generating capacity spread across an area of approximately 700 square miles in Olga, ND is assumed [9, 13, 25]. Based on the wind capacity and seasonability effect of both locations, it is determined that an average capacity factor of 40% for the wind generators in both locations results in annual average generation of approximately 35 Million MWh. The cost assumptions of the wind farm installations in North Dakota, converter/inverter stations, AC lines, and the HVDC lines are set based on the year 2010 component installed capital costs, in $US 2002 as shown in Table 1 [26-27].

The annual energy production (AEP) considering an average wholesale price of $0.034/kWh for electric energy delivered to northern California, the total annual revenues is calculated as $1.1 Billion. The total capital cost as shown in Table 1 is approximately $10.9 Billion. The ratio of total cost to annual revenues results in a payback factor 9.9 years. This number may be rounded to 10 years to include power transmission losses, annual right-of-way, maintenance, transformers, control schemes, and other expenditures. This payback amount makes the overall project promising as well as increasing electrical power reliability of the state of California. Therefore this scheme should be analyzed in greater detail, using a net cash flow analysis for Internal Rate of Return (IRR) and Net Present Value (NPV). Keith and Leighty have done a detailed study covering a number of HVDC scenarios and their economical analysis [26].

VII. Conclusion

This study has shown the feasibility of establishing two new wind farms of 5,000 MW power capacity each at Olga 3 and Olga 5 wind sites in the state of North Dakota. The study has also shown that, considering a realistic value of 40% of wind capacity factor in the region, feasibility of an average power generation of 4,000 MW from wind farms can be converted to HVDC in North Dakota, and transmitted to northern California by two parallel bipolar 1,700 mile long HVDC lines. The HVDC lines are co-located on a single set of towers. This proposed project with a payback amount of 10 years may bring thousands of new job opportunities in all the states involved and provide an excellent relief to California's growing power demand.

Table 1 . Cost Analysis [26]

	Unit Cost	Units	Total ($ Billion)
Wind Farms	$900/kW	10,000MW	$9.0 B
HVDC Lines	$500,000 per mile	1700 miles	$0.85 B
Converter/ Inverter Stations	$130/kW	4000 MW*2	$1.04 B
		Total Cost:	**$10.89 B ~ $10.9 B**

Total Generation:	35,040,000
HVDC Assumptions	
Converter Losses	0.9%
Total Line Losses	6.4%
End Use Gen. Efficiency	n/a
Total Energy Losses:	2,557,920
Overall Efficiency:	93.2%
Electricity Prices	
Price	$0.034/kWh
Sales and Revenues	
Total MWh Sold:	32,482,080
Total Revenues:	$1.1 B
Revenue per MWh:	$33.86

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