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Remote Power Generating Systems WHIT Using Low Frequency Transmission

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Abstract— the goal of this research is to evaluate alternative transmission systems from remote wind farms to the main grid using low-frequency AC technology. Low frequency means a frequency lower than nominal frequency (60/50Hz). The low-frequency AC network can be connected to the power grid at major substations via cyclo-converters that provide a low-cost interconnection and synchronization with the main grid. Cyclo-converter technology is utilized to minimize costs which result in systems of 20/16.66 Hz (for 60/50Hz systems respectively). Low frequency transmission has the potential to provide an attractive solution in terms of economics and technical merits. The optimal voltage level selection for transmission within the wind farm and up to the interconnection with the power grid is investigated. The proposed system is expected to have costs substantially lower than HVDC and conventional HVAC systems. The cost savings will come from the fact that cyclo-converters are used which are much lower in cost than HVDC. Other savings can come from optimizing the topology of the wind farms. Another advantage of the proposed topologies is that existing transformers designed for 60 Hz can be used for the proposed topologies (for example a 345kV/69 kV, 60Hz transformer can be used for a 115 kV/23kV, 20 Hz system). The results from this research indicate that the use of LFAC technology for transmission reduces the transmission power losses and the cost of the transmission system.

Keywords— Low frequency, Cyelo Converter, Wind Farm Connections, wind frame topology, wind system configuration, series and parallel wind frame, voltage level selection.

INTRODUCTION

Renewable sources of energy are widely available and proper utilization of these resources leads to decreased dependence on the fossil fuels. Wind is one such renewable source available in nature and could supply at least a part of the electric power. In many remote locations the potential for wind energy is high. Making use of the available wind resources greatly reduces the dependence on the conventional fuels and lowers the emission rates. There are a few problems associated with the wind which makes the wind energy more expensive than other forms of electric power generation. The two main issues are: (a) Large wind farms are located in remote locations which make the cost of transmission of wind power costly, and (b) the intermittent supply of power due to the unpredictability of the wind that results in lower capacity credits for the operation of the integrated power system. These issues are addressed by designing alternative topologies and transmission systems operating at low frequency for the purpose of decreasing the cost of transmission and making the wind farm a more reliable power source. The use of DC transmission within the wind farm enables the output of wind generators to be rectified via a standard transformer/rectifier arrangement to DC of appropriate kV level.

Research Objectives

- Literature study of previous research on low frequency AC transmission and wind farm topologies.
- Design of alternate topologies.
- Calculation of optimal transmission voltage levels for different topologies.
- Modeling the system using WinIGS-F software.

Technologies for Wind Farm Power Transmission

The possible solutions for transmitting power from wind farms are HVAC, Line commutated HVDC and voltage source based HVDC (VSC-HVDC). Low frequency AC transmission (LFAC) is particularly beneficial in terms of cost savings and reduction of line losses [4] in cases where the distance from the power generating stations to the main power grid is large. The use of fractional frequency transmission system (FFTS) for offshore wind power is discussed in [6]. The author proposes LFAC as an alternative to HVAC and HVDC technologies for a short and intermediate transmission distances. HVAC is more economical for short transmission distances.

For longer distances, HVAC has disadvantages like increase in the cable cost, terminal cost and charging. HVDC transmission systems and wind farm topologies are discussed in [12]. HVDC being a matured technology is used for longer distances. Compared to HVDC, the LFAC system reduces the usage of an electronic converter terminal which reduces the investment cost. HVDC technology is used only for point-to-point transmission [11], and LFAC can be used for similar networks as AC transmission. Further, VSC-HVDC replaces the thyristors with IGBTs and is considered to be the most feasible solution for long distance transmission. However, addition of converter stations on both sides of the transmission line increase the investment cost of the VSC-HVDC system [7] compared to LFAC. Hence, due to the limitations of the HVAC and HVDC the proposed LFAC is used in the design of transmission systems. The use of LFAC can be extended to long transmission distances. Cyclo converter technology is used for converting the AC of nominal frequency to AC of one third frequency i.e. 16.67 Hz/20 Hz for a 50 Hz/ 60 Hz transmission system`. Several advantages of the LFAC are identified. The transmission system used for conventional AC system can be used for LFAC without any modifications and the LFAC system increases the transmission capacity.

Wind system configuration 1: AC wind farm, Nominal frequency, Network connection: Two different types of AC wind farms referred in this thesis are radial and network connections. Radial wind farms are suitable for small wind farms with a short transmission distance. In a small AC wind farm, the local wind farm grid is used both for connecting all wind turbines in a radial fashion and transmitting the generated power to the wind farm grid interface. Network connected wind farms are usually large AC wind farms where the local wind farm grid has a lower voltage level than the transmission system. The wind system configuration 1 shown in figure 3.2.1 has network connection of wind turbines and AC power collection system.

Wind System Configuration 2: AC Wind Farm, AC/DC Transmission, And Network Connection: The wind system configuration 2 shown in figure 3.2.2 is similar to the wind system configuration 1 except for the transmission part from the collector substation to the main power grid. AC transmission is replaced by DC transmission in this configuration. Nominal frequency transmission is adopted within the wind farm. This wind farm is referred to as AC/DC wind farm. This type of system does not exist today, but is frequently proposed when the distance to main grid is long.

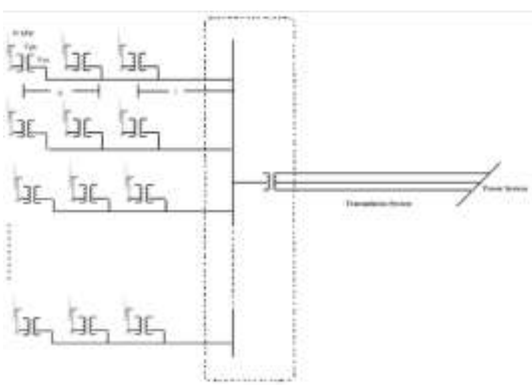


Figure 3.2.1: Wind system configuration1

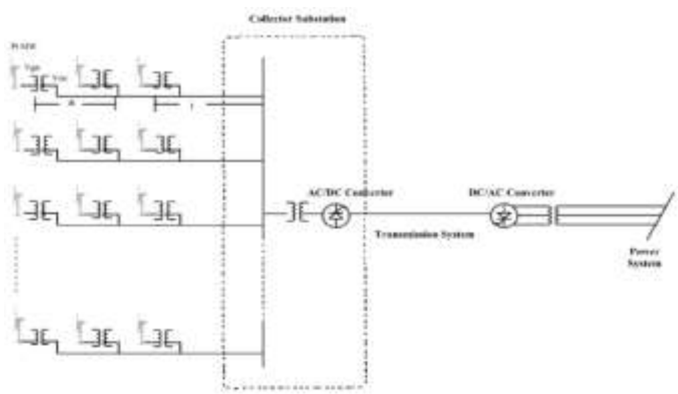
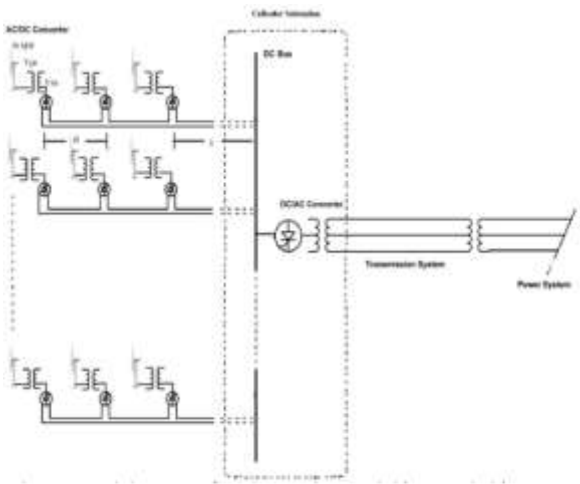


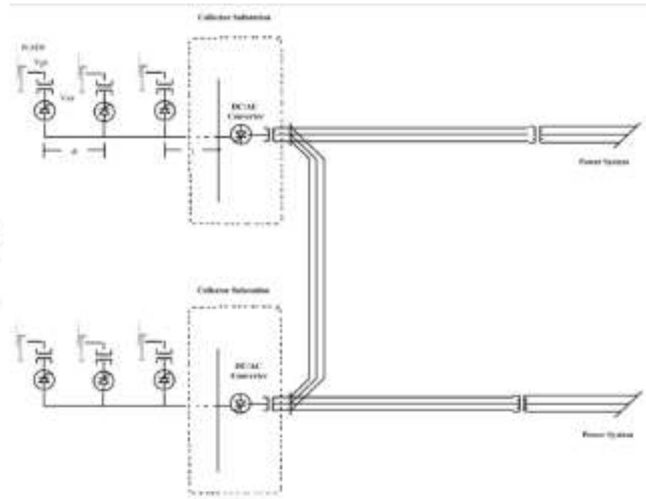
Figure 3.2.2: Wind system configuration 2

Wind system configuration 3: Series DC Wind farm, Nominal frequency, Network connection: The wind system configuration 3 has a DC power collection system. Wind turbines are connected in series and each set of series connected array is connected to the collection point. Using DC/AC converters, AC of suitable voltage level and nominal frequency is generated. Voltage is stepped up and the power is transmitted to the interconnection point at the power grid by a high voltage transmission line.

Wind System Configuration 4: Parallel DC Wind Farm, Nominal Frequency, Network Connection: Wind system configuration 4 differs from the wind system configuration 3 in the local wind farm design. Here a number of wind turbine systems are connected in parallel and each set of parallel connected wind turbines are connected to a collection point. Using DC/AC converters, AC of suitable voltage level and nominal frequency is generated. At the collection point voltage is stepped up by means of a transformer and the power is transmitted to the interconnection point at the power grid by a high voltage transmission line. Two small sized wind farms are interconnected via a transmission line to ensure reliable supply of power to the main grid in the event of fault or maintenance shut down in any one of the wind farms by transferring power generated from the other wind farm.



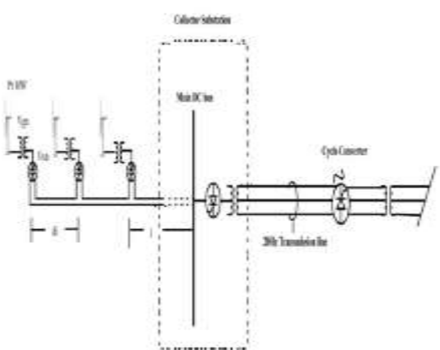
Wind system configuration 3: Series DC Wind farm



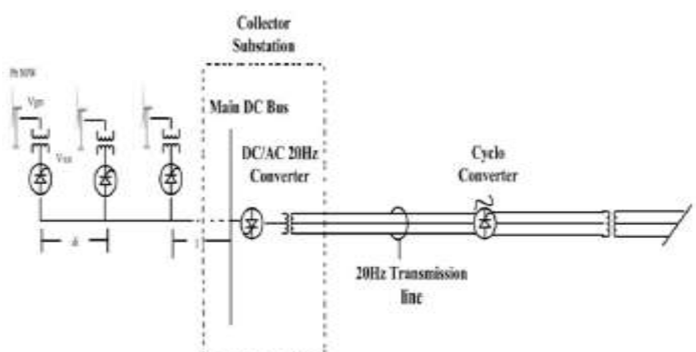
Wind system configuration 4: Parallel DC Wind farm

Wind System Configuration 5: Series DC Wind Farm, Low Frequency Radial AC Transmission: The wind system configuration shown in figure 3.2.5 has a DC wind farm. Here a number of wind turbine systems are connected in series and each series string is connected to a collection point. An inverter is used to convert DC to AC of low-frequency preferably one third the nominal power frequency at the collection point. The voltage is raised to higher kV levels by means of a transformer (standard transformers are used with appropriately reduced ratings for the low frequency). The power is transmitted to the main power grid via lines operating at low frequency. Using cyclo-converters the low frequency is converted to power frequency before connecting to the main power grid.

Wind System Configuration 6: Parallel DC Wind Farm, Low Frequency, Radial Transmission: Wind system configuration 6 is similar to the wind system configuration 5. Here the difference is that the wind turbines are connected parallel to each other and to the collection point. Parallel connection of wind turbines leads to same voltage across the terminals of all the wind turbine systems. The generated power is converted to low-frequency AC using inverter and transmitted over long distances to the power grid. Cyclo-converter technology is used to convert the low frequency to nominal frequency before connecting the system to the main power grid.



Wind system configuration 5: Series DC wind farm



Wind system configuration 6: Parallel DC Wind Farm

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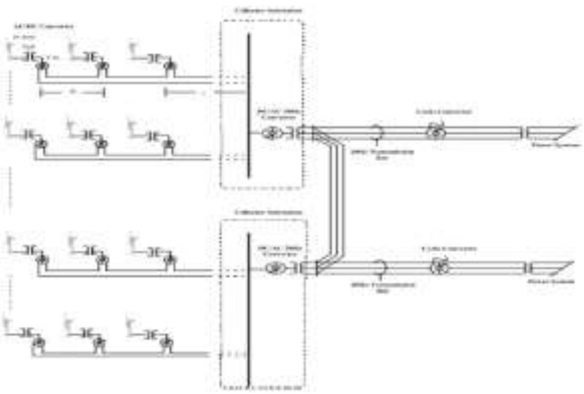
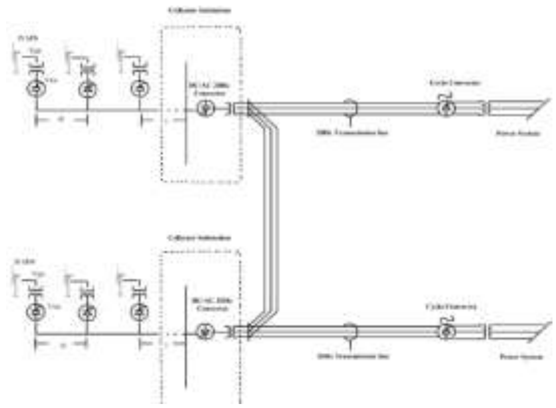


Wind system configuration 7: Series DC wind Farm



Wind system configuration 8: Parallel DC wind Farm

Wind System Configuration 7: Series DC Wind Farm, Low Frequency AC Transmission Network: Here a number of wind turbine systems are connected in series and each set of series connected array is connected to a collection point. At the collection point DC is converted to low frequency AC by means of inverters. The transmission of power up to the main power grid is by means of a network of transmission lines operated at low frequency. The low frequency AC system is connected to the power grid by means of cyclo-converters.

Wind System Configuration 8: Parallel DC Wind Farm, Low Frequency AC Transmission Network: Wind system configuration 8 has a number of wind turbine systems connected in parallel and each set of parallel connection of wind turbine systems are connected to a collection point. From the collection point to power grid system is identical to wind system configuration 7.

VOLTAGE LEVEL SELECTION: This section provides analysis and results that determine the optimal transmission voltage used in the alternative wind transmission systems up to the main DC bus. The optimal kV level for transmission within the wind farm is selected by evaluation of the total costs consisting of operational costs (mainly losses) and annualized investment cost. The cost of the auxiliary equipment is not considered. The optimal kV level is selected on the basis of minimal total cost consisting of operating costs (mainly transmission loss) and investment cost.

Voltage calculation-Wind system configuration 5: Series DC wind farm, Low frequency radial AC transmission: Wind system configuration 5 has a series DC wind farm as shown in figure 4.1 where mi wind turbines are connected in series to obtain the suitable transmission voltage. The wind turbine systems are assumed to be identical, thus resulting in same voltage and current through them. A wind farm rated 30 MW consisting of 10 wind turbines each rated 3 MW is considered. The transmission voltage for calculation purpose is selected as 35 kV. Thus, the nominal high side transformer voltage for the wind turbines is 3.5 kV. The optimal transmission voltage is obtained by plotting the values obtained from the calculation of loss and the annual investment cost of the cable and converter for different values of the transmission voltage. The resistance of the chosen cable is approximately 0.0153 ohm/ 1000 ft.

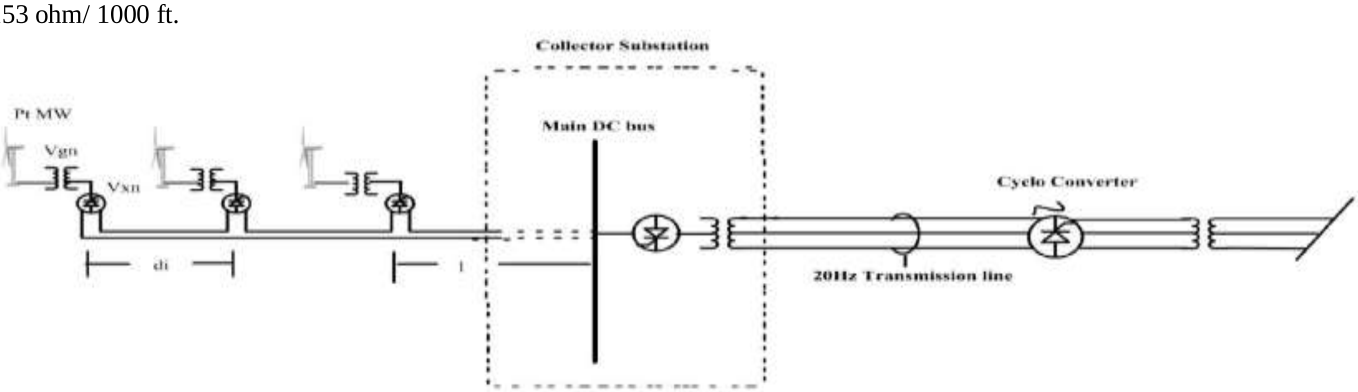


Figure 4.1: Wind farm configuration 1: Series DC wind farm, radial connection

Calculation of transmission loss (up to the main DC bus) ($/yr): The following equations are used to determine the transmission loss with in the wind farm.

$$P_t = I_{dc} V_{xn}$$

$$V_{xn} = \frac{V_{dc}}{m_i}$$

$$I_{dc} = \frac{P_t}{V_{xn}}$$

$$R = 2r(l + (m_i - 1)d)$$

$$P_L = I_{dc}^2 R$$

Where,

n_f : Number of radial feeders = 1

m_i : Number of wind turbines in radial feeder i = 10

d_i : Distance between adjacent wind turbines in feeder i (feet) = 500 ft

l : Distance from the last wind turbine to the collection point = 600ft

P_t : Power rating of the wind turbine (MW) = 3 MW

V_{gn} : Nominal generator voltage = 0.575 kV

V_{dc}: Nominal DC bus voltage = 35 kV

V_{xn} : Nominal high side transformer voltage = 3.5 kV

R,X : Positive sequence resistance and reactance of medium voltage cable per unit length (ohms/meter)

I_{dc} : DC current in the DC circuit [Amperes]

r : Resistance of cable per unit length = 0.0153 ohms/1000ft

P_L : Transmission power loss [MW]

Substituting the above values in (1), (2), (3), (4) and (5) we get:

I_{dc} = 857 A

R = 0.156 ohms

P_L = 0.1145 MW

C: Cost of electricity = $100/ MWh

$$Loss\ in\ \$/yr = (8760)\, n_f C P_L$$

This formula assumes that the wind farm operates continuously at maximum power which is unrealistic. The capacity factor of a wind turbine is approximately 30% [1]. Hence the resultant Loss in $/yr is multiplied by 0.3. Therefore, Loss = $ 30,110 /yr.

Calculation of Cost of cable and the converter equipment in $/yr: The acquisition cost of the cable is $ 18.5 /ft. To calculate the cost of cable required for the entire wind farm, the length of the cable is calculated. Multiplying the acquisition cost of cable by the total length of the cable gives the acquisition cost of the cable for the entire wind farm in $.

$$L = 2 n_f (l + (m_i - 1)d)$$

$$CCost = n_f L\, ACost$$

L: Total length of the cable up to the collection point [feet]

CCost: Acquisition cost of cable for entire wind farm [$]

ACost: Acquisition cost of the cable per feet = $ 18.5 /ft

Total length of cable, L = 10,200 ft

Therefore, acquisition cost of the cable, CCost = $ 188,700/yr.

The cost of converter is given by

$$Cost_{conv} = (0.5)\, m_i n_f\, Cost_{inv} \left(1 + \left(\frac{V_{xn}}{690} \right)^{0.5} \right)$$

$Cost_{conv}$: Cost of converter [$]

$Cost_{inv}$: Cost of inverter = 14,692 $

The above calculation gives the acquisition cost of converters to be $238,907. Assuming an interest rate of 6% and the life time of the cable and the converter to be 20 years, the annual amortization is calculated. Acquisition cost of the cable and the converters is $ 427,607.

$$A = P \frac{i(1+i)^n}{(1+i)^n - 1}$$

P: Acquisition cost of cable and converter = 427,607 $

A: Annual investment for cable and converter [$/yr]

i: Interest rate= 6%

N: Life time = 20 years

Thus, the annual investment for cable and converter is $ 37,244 /yr. For determining the optimal operating voltage, Vdc vs. Loss ($/yr) and Vdc vs. Annual investment for cable and converter ($/yr) are plotted. The optimal voltage level is determined by the lowest point of the curve obtained by adding the Loss ($/yr) and Annual investment cost ($/yr) as shown in figure 4.2.

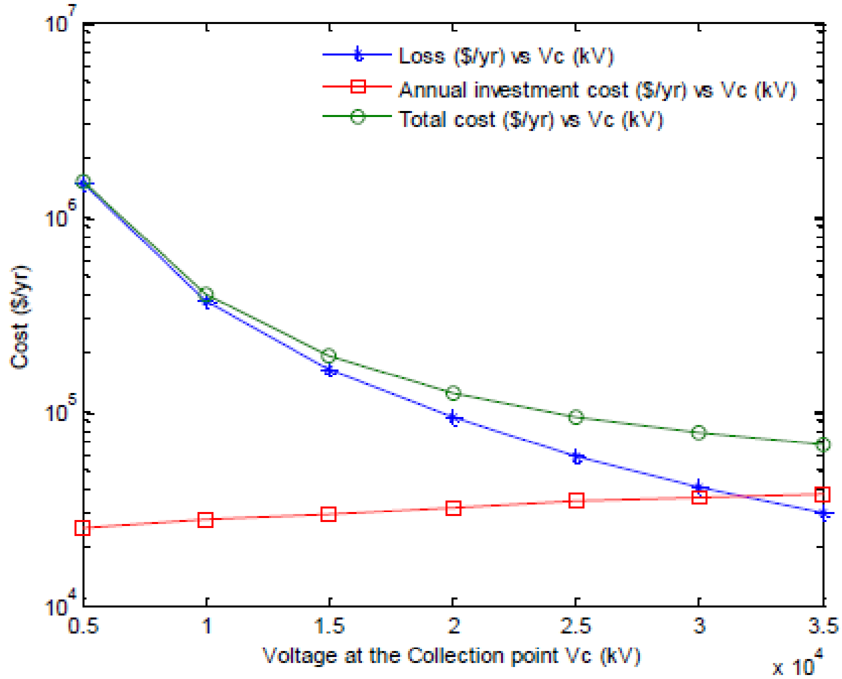


Figure 4.2: Plot of voltage at Che main DC bus vs. total cost for mi=10, Pt = 3MW

From the plot in figure 4.2 it can be seen that for the wind farm rated 30 MW having 10 wind turbines the optimal voltage would be around 35kV. As the voltage level further increases the transmission power loss decreases but the cost of the cable and the converter increases. The plots of annual investment cost vs. Vdc and loss vs. Vdc intersect 23 at 32 kV, from that point the annual investment cost goes on increasing. The optimal voltage is obtained by determining the lowest point on the graph obtained by adding the annual investment cost and the loss in $/yr. The x coordinate of the point is the optimal transmission voltage which is 35 kV in this case. For different wind turbine ratings, cable size and the wind farm size the optimal level of voltage is calculated in a similar fashion as shown above.

STEADY STATE ANALYSIS

Wind Farm Modeling

Performance of a multiphase system under steady state conditions is analyzed using WinIGS-F program. Wind system configurations 1, 4 and 8 are modeled to analyze the system performance.

Wind system configuration 1_ model 1: In the system shown in figure 5.1 the wind farm is connected to a transmission line 54 miles long. Wind farm consists of 3 radial feeders with 4 wind turbines on each radial feeder. All the wind turbines are identical and rated 2.7 MW each. A three phase two winding transformer rated 3 MVA is connected to each wind turbine to raise the voltage to 25 kV. The power generated at each wind turbine is collected at the collector substation. A transformer rated 36 MVA with primary voltage of 25 kV and secondary voltage of 115 kV is installed at the collector substation. At the end of the transmission line a three phase constant electric load and a slack generator are connected.

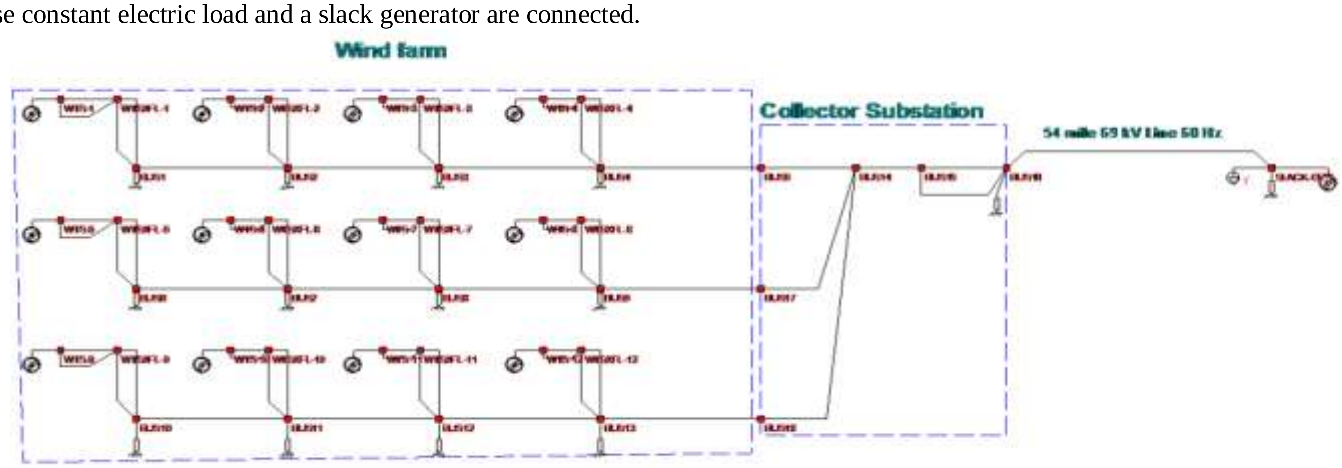


Figure 5.1 Wind system configuration 1 (60 Hz transmission)

Total power loss during transmission is obtained by running the model and it is 1.1925 MW for this case.

Wind system configuration 4_ model 2: The wind system configuration 4 is modeled as shown is figure 5.3. It has two small wind farms located at a distance away from each other. This model is similar to a scenario where there are two wind farms in different geographical areas and power is collected at the collector substation and transferred over long distances to the main grid. Under any disturbance to the generation of power in one of the wind farms the other wind farm supplies the power.

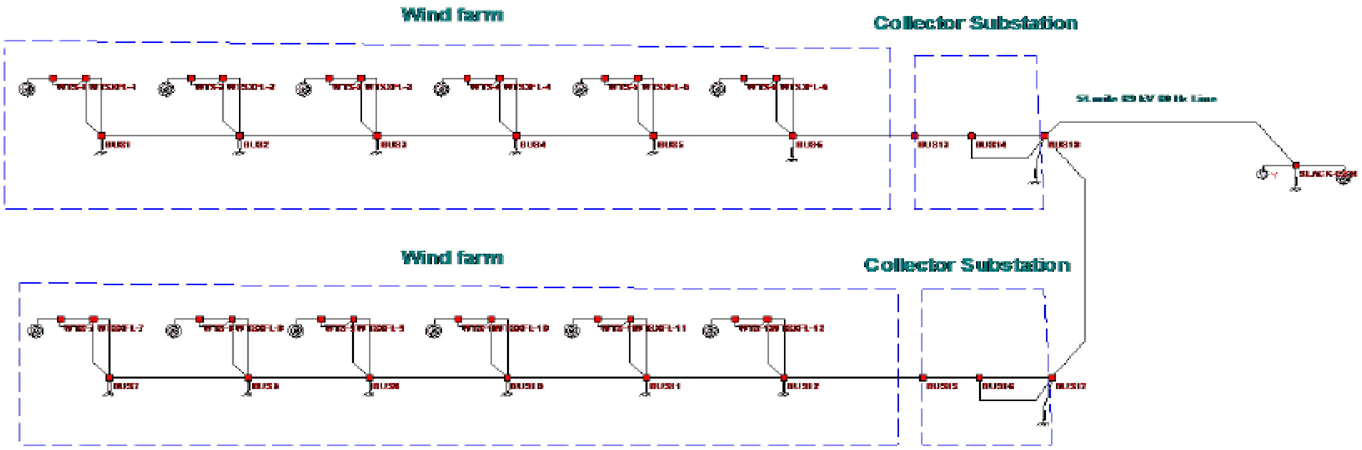


Figure 5.3 Wind system configuration 4 (60 Hz transmission)

Each wind turbine is rated 2.7 MW with 25 kV operating voltage within the wind farm. The operating voltage of the long distance transmission line from the collector substation to the main grid considered here is 69 kV.

Wind system configuration 8 _ model 3: The wind system configuration 8 is modeled as shown in figure 5.4. A 20 Hz transmission line, 54 miles long and operating at 69 kV is modeled in this case.

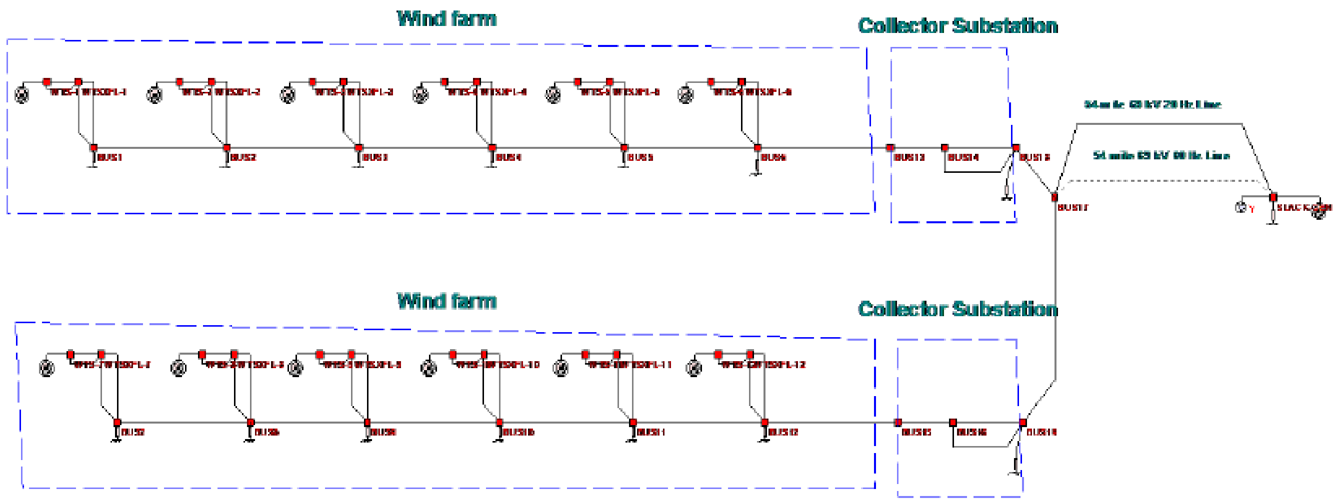


Figure 5.4 Wind system configuration 8 (20Hz transmission)

the transmission line parameters used for 60 Hz transmission can be used for 20 Hz transmission.

Operating voltage (kV)	Transmission length (miles)	Power loss (MW) 20 Hz transmission
69	54	0.3395
	100	0.3398
115	54	0.1586
	100	0.1589
138	54	0.1281
	100	0.1283

Table 5.3 Transmission power loss for wind system configuration 8 (20 Hz transmission)

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CONCLUSIONS

Geographical locations that are suitable for wind farm development are in remote locations far from the main transmission grid and major load centers. In these cases, the transmission of wind power to the main grid is a major expenditure. The potential benefit of the LFAC technology presented in this study is the reduction in the cost of the transmission system. This makes the economics of the wind energy favorable and increases the penetration of wind power into the system. LFAC technology is used for transmission from the collector substation to the main power grid. The thesis presents alternate topologies suitable for various geographical locations and configurations of the wind farm. The optimal operating voltage of the transmission lines within the wind farm is calculated for all the cases. The optimal voltage is computed considering the cost of the cable, converter equipment and the power loss due to transmission. The preliminary study results show that higher the operating voltage lower will be the transmission losses and with the increase of the transmission distance the transmission losses on the line increase. The results obtained by modeling the wind system configurations point towards higher transmission losses in 60 Hz transmission compared to 20 Hz transmission.

REFERENCES:

[1] X. Wang, H. Dai, and R. J.Thomas, “Reliability modeling of large wind farms and associated electric utility interface systems” IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, no. 3, March, 1984, pp. 569-575.

[2] R.J.Thoma, Phadke, A.G. Phadke, C. Pottle, “Operational Characteristics of A Large Wind-Farm Utility- System with A Controllable AC/DC/AC Interface” IEEE Transaction on Power Systems, Vol. 3, No.1. February 1988.

[3] An-Jen Shi, Thorp J., Thomas R., “An AC/DC/AC Interface Control Strategy to Improve Wind Energy Economics”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 12. December 1985.

[4] T. Funaki, “Feasibility of the low frequency AC transmission,” in *Proc. IEEE PES Winter Meeting*, Vol. 4, pp. 2693–2698, 2000.

[5] W. Xifan, C. Chengjun, and Z. Zhichao, “Experiment on fractional frequency transmission system,” *IEEE Trans. Power Syst*., Vol. 21, No. 1, pp. 372–377, Feb. 2006.

[6] N. Qin, S. You, Z. Xu, and V. Akhmatov, “Offshore wind farm connection with low frequency AC transmission technology,” in *Proc. IEEE PES General Meeting*, Calgary, Alberta, Canada, 2009.

[7] S. Lundberg, “Evaluation of wind farm layouts,” in *Nordic Workshop on Powerand Industrial Electronics (NORPIE 2004)*, Trondheim, Norway, 14-16 June, 2004.

[8] S. Lundberg, "Wind farm configuration and energy efficiency studies series DC versus AC layouts," Thesis, Chalmers University of Technology 2006.
[9] N. Kirby, L. Xu, M. Luckett, and W. Siepmann, “HVDC transmission for large offshore wind farms,” *Power Engineering Journal*, vol. 16, no. 3, pp. 135 –141, June 2003.
[10] C. Skaug and C. Stranne, “HVDC wind park configuration study,” Diploma thesis, Chalmers University of Technology, Department of Electric Power Enginering, G¨oteborg, Sweden, October 1999.
[11] Lazaros P. Lazaridis, “Economic comparison of HVAC and HVDC solutions for large offshore wind farms under special consideration of reliability,” Thesis, KTH.
[12] F. Santjer, L.-H. Sobeck, and G. Gerdes, “Influence of the electrical design of offshore wind farms and of transmission lines on efficency,” in *Second International Workshop on Transmission Networks for Offshore Wind Farms*, Stockholm, Sweden, 30-31 March, 2001.
[13] R. Barthelmie and S. Pryor, “A review of the economics of offshore wind farms,” *Wind enginering*, vol. 25, no. 3, pp. 203–213, 2001.
[14] J. Svenson and F.Olsen, “Cost optimising of large-scale offshore wind farms in the danish waters,” in *1999 European Wind Energy Conference*, Nice, France, 1-5 March, 1999, pp. 294–299