Analysis of Medium Voltage DC Offshore Wind Farm Distribution System

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Abstract—---Popularity of the offshore wind farms in recent years has been increased because the wind resource in offshore is higher with uniform wind speed and availability of large sea area. Most of the offshore wind farms have MVAC (Medium voltage Alternating Current) distribution system. In this paper MVDC (Medium Voltage Direct Current) distribution system is proposed and the performance of this is compared with its equivalent MVAC distribution system. To evaluate performance of any radial connected distribution system load flow solution is essential. In this paper direct load flow method is used which directly solves load flow of offshore wind farm distribution system using KVL and KCL. The advantage of this algorithm is that it can be used with any type of variable speed generators.Further to validate computer simulations are carried out for 80 MW MVDC based wind farm distribution systems using MATLAB.

Index Terms— **wind energy; PMSG; MVAC; MVDC..**

1. INTRODUCTION

TODAY there is concern about greenhouse effect. This has lead to more investments in renewable energy sources in order to decrease it. Among them windenergy is the fastest and eco-friendly renewable energy source. Wind energy installations have gone from being small units erected one by one to larger units erected in groups. Today wind farm up to a size of 160 MW have been built and several plants of 1000 MW exist[1].These larger wind farms are mainly considered to be located out in sea, preferably at such a distance out in the sea that they cannot be observed from the shore. In general, offshore wind farm located more than 60-100 km away from the onshore which require HVAC/HVDC interconnector, individual transformers to boost the low voltage of wind generator to medium voltage, undersea cables to collect energy from the wind farm, high voltage transformer to boost the voltage and HVDC converter. For long distance transmission HVDC is more economical than HVAC due their lesser losses [2].

Various generators such as Permanent Magnet Synchronous Generator (PMSG) & Doubly Fed Induction Generator) DFIG (i.e. variable speed) and SCIG (i.e. fixed speed) are used in wind energy conversion system (WECS) to extract power generated for wide speed range (i.e. 100 %) and gear box can be eliminated.

Different offshore wind farm distribution systems (WFDS) topologies are discussed in [4]. Most of these distribution systems topologies use MVAC to interconnect the generators.By replacing the inverter and transformer in MVAC with DC/DC converter, the MVDC based offshore WFDS is formed [5]. In this paper the performance analysis of both MVAC and MVDC transmission based offshore WFDS are presented.

In order to evaluate the performance of any radial distribution system, load flow solution is necessary. Traditional load flow methods used in transmission system such as Gauss-Seidel and Newton-Raphson techniques fails to meet the requirements in both performance and robustness aspects in the distribution system applications [6]. In particular, the assumptions necessary for the simplifications used in the standard Fast-Decoupled load flow method often are not valid in distribution system. The load flow presented in [6, 7] takes advantages of the radial system. Nevertheless the algorithm solves the distribution flow by neglecting the shunt capacitance of lines. On other hand in offshore wind farms underground cables are used for transmission system whose capacitance effect is predominant and hence it cannot be neglected.

This paper proposes a direct load flow method for offshore WFDS by considering shunt capacitance in which KCL and KVL are used to solve the load flow directly. Further, the performance of MVAC and MVDC based WFDS are evaluated independently and compared over a wide wind speed range using steady state analysis. In this load flow algorithm the transmission line (XLPE underground cable) is modelled as π model and all the generators are modelled as PQ buses [8]. Same XLPE cable is used for both MVAC and MVDC transmission within the distribution system.

Moreover, the performance of MVDC based WFDS is done with the proposed direct load flow algorithm. The paper is organized as follows: In section II the steady state modeling of wind energy conversion system is explained. The direct approach algorithm used in WFDS is discussed in section III. The performance analysis for both MVDC based offshore WFDS is carried out using MATLAB and results are presented in section 4.

2. SYSTEM MODELLING

In this paper an 80 MW offshore WFDS which contain 40 PMSG based generators each of 2 MW is considered with MVDC distribution system and these are shown in Fig.1. In order to analyze the performance of both the systems, the performance characteristics such as voltage profile, total system losses, generated real power and efficiency for different wind speeds are studied. In MVDC, PMSG is connected to AC-DC converter and then to DC-DC converter. Here the collecting point voltage is taken as 33 kV in both the cases.

2.1 Wind Turbine Modelling

The power available in wind is given by [9],

$$P_w = \frac{1}{2}\rho A V_w^3 \quad (1)$$

where ρ is the air density, A is swept area and V_w is velocity of wind.

The wind turbine can recover only a part of that power which is given by,

$$P_{mech} = \frac{1}{2}\rho \pi R^2 V_w^3 C_p \quad (2)$$

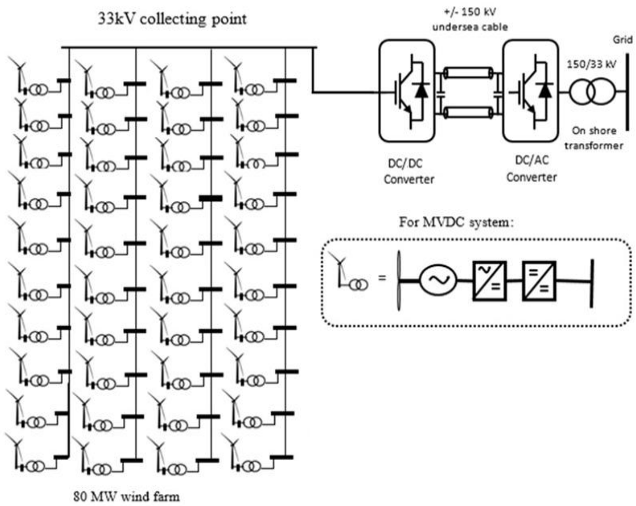


Fig. 1 MVDC based offshore wind farm distribution system

where C_p is the power coefficient i.e. effectiveness of the wind turbine in the transformation of kinetic energy of the wind into mechanical energy.

The power coefficient can be written as function of λ and β,

$$C_p(\lambda,\beta) = 0.22\left[\frac{116}{\lambda} - 0.4\beta - 5\right]e^{-\frac{12.5}{\lambda}} \quad (3)$$

where β is the pitch angle and λ is the tip speed ratio which is given by,

$$\lambda = \frac{\omega_m R}{V_w} \quad (4)$$

where ω_m is the angular mechanical speed. In (3) considering β = 0, $C_p(\lambda)$ becomes

$$C_p(\lambda) = 0.22\left[\frac{116}{\lambda} - 5\right]e^{-\frac{12.5}{\lambda}} \quad (5)$$

Taking $d(C_p(\lambda))/d\lambda=0$, at λ_{opt}=8.123 $C_{p,max}$ = 0.4382. From (4), optimum rotor speed ω_{opt} is given by,

$$\omega_{opt} = \frac{\lambda_{opt} V_w}{R} \quad (6)$$

Thus the optimum rotating speed of the turbine is calculated when R and V_w are known to track the maximum power from wind.

2.2 Steady state modelling of PMSG

The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind. PMSG can generate power at any wind speed between cut in and cut out speed.

The steady state model generally used for the PMSG as shown in Figure 2 is the *d-q* axes 'Park' model [9]. By considering only the fundamental harmonic of the flux distribution in the air-gap of the machine and by neglecting the homopolar component, theory of the space vector gives the dynamic equations of the stator voltages as below.

$$\left.\begin{aligned} V_{sd} &= R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_e \varphi_{sq} \\ V_{sq} &= R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_e \varphi_{sd} \end{aligned}\right\} \quad (7)$$

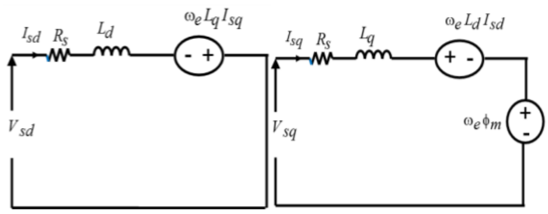


Fig. 2 Equivalent circuit model of PMSG (a) d- axis (b) q-axis

The stator fluxes are given by,

$$\left.\begin{aligned} \varphi_{sd} &= L_d I_{sd} + \phi_m \\ \varphi_{sq} &= L_q I_{sq} \end{aligned}\right\} \quad (8)$$

where, ϕ_m is the flux linkage of the permanent magnet

L_d and L_q are the d-q axes inductances

I_{sd} and I_{sq} are the d-q axes stator currents

V_{sd} and V_{sq} are the d-q axes stator voltages

φ_{sd} and φ_{sq} are the d-q axes flux linkages

V_{sd} and V_{sq} are the stator and rotor voltages

R_s is the stator resistance

ω_e is the synchronous speed of the machine in rad/s.

Combining equations (7) and (8), we can obtain:

$$\left.\begin{aligned} V_{sd} &= R_s I_{sd} + L_d \frac{dI_{sd}}{dt} - \omega_e L_q I_{sq} \\ V_{sq} &= R_s I_{sq} + L_q \frac{dI_{sq}}{dt} + \omega_e L_d I_{sd} + \omega_e \phi_m \end{aligned}\right\} \quad (9)$$

The stator active and reactive powers are given by

$$P_s = \frac{3}{2}(V_{sd} I_{sd} + V_{sq} I_{sq}) \text{ and } Q_s = \frac{3}{2}(V_{sq} I_{sd} - V_{sd} I_{sq}) \quad (10)$$

Finally, the efficiency of the machine is obtained as

$$\eta = \frac{P_s}{P_{mech}} \quad (11)$$

2.3 Modelling of Transmission Line

The Cross Linked Poly Ethylene (XLPE) underground cables are used for transmission within offshore wind farms. XLPE parameters are specified in Appendix. In DC transmission only its equivalent DC resistance is considered. The transmission line is modelled as π model as given in Figure 3.

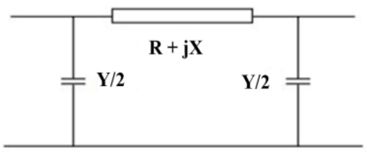


Fig. 3 Representation of transmission line

2.4 Efficiencies of Converters

In MVDC system AC-DC converter and DC-DC converter is considered. The converter losses are divided into two categories, switching and conduction losses. Losses in converters are calculated using analytical equations given in [10, 11]. Parameters of converters are specified in Appendix.

3. ALGORITHMS DEVELOPMENT

The load flow algorithm for the distribution system (Fig.1 and Fig.2) is developed based on two decoupled matrices Bus Injected to Branch Current (BIBC) and Branch Current to Branch Voltage (BCBV). In this algorithm, KCL and KVL used to form the BIBC & BCBV matrices and simple matrix multiplication is utilized to obtain the load flow solution.

In this load flow algorithm all the generators are modelled as P-Q bus model [8]. The reactive power injected to the local bus is maintained at zero in load flow analysis since GSC is controlled to operate at unity power factor.

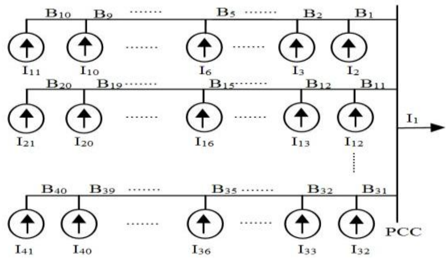


Fig. 4 Equivalent current injections representation

The transmission line (XLPE underground cable) is modelled as π model [12]. The power injections can be converted to the equivalent current injections as shown in Figure 4 and the current at each node can be found from the relation,

$$I_i = \frac{P_i + jQ_i}{V_i^*} + Y_i V_i \quad (12.a)$$

where, i = 3,4,5....n+1, where n= no of buses

i ≠ 10n+2 ,n=1, 2...r, where r no of radial branches

For i =10n+2, where n=1, 2...r

$$I_i = \frac{P_i + jQ_i}{V_i^*} + \frac{Y_i}{2} V_i \quad (12.b)$$

The BIBC matrix can be obtained by applying KCL at all buses in the distribution system (Fig.5).

$$\left.\begin{aligned} B_1 &= I_2 + I_3 + \ldots + I_{11} \\ &. \\ B_{39} &= I_{40} + I_{41} \end{aligned}\right\} \quad (13.a)$$

$$B_{40} = I_{41}$$

The above equations can be written in matrix form as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ . \\ . \\ B_{39} \\ B_{40} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & . & . & 0 & 0 \\ 0 & 1 & 1 & . & . & 0 & 0 \\ 0 & 1 & 1 & . & . & 0 & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & 1 & 1 \\ 0 & 0 & 0 & . & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ . \\ . \\ I_{40} \\ I_{41} \end{bmatrix}$$

$$[B] = [BIBC] * [I] \qquad (13.c)$$

where [B] is branch currents matrix and [I] is bus currents matrix. The constant BIBC matrix contains values of 0 and 1 only.

Similarly, the BCBV matrix can be obtained by applying KVL to the distribution system and is given by,

$$\left.\begin{aligned} V_2 &= V_1 - B_1 Z_{1,2} \\ V_3 &= V_2 - B_2 Z_{2,3} \\ &. \\ V_{41} &= V_{40} - B_{40} Z_{40,41} \end{aligned}\right\} \qquad (14.a)$$

The above equations can be written as,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ . \\ . \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ . \\ . \\ V_{39} \\ V_{41} \end{bmatrix} = \begin{bmatrix} Z_{1,2} & 0 & 0 & . & . & 0 & 0 \\ Z_{1,2} & Z_{2,3} & 0 & . & . & 0 & 0 \\ Z_{1,2} & Z_{2,3} & Z_{3,4} & . & . & 0 & 0 \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & Z_{39,40} & 0 \\ 0 & 0 & 0 & . & 0 & Z_{39,40} & Z_{40,41} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ . \\ . \\ B_{39} \\ B_{40} \end{bmatrix} \qquad (14.b)$$

$$[\Delta V] = [BCBV] \times [B] \qquad (14.c)$$

From equations (13.c) and (14.c) we obtain

$$[\Delta V] = [BCBV] \times [BIBC] \times [I] \qquad (15.a)$$

$$[\Delta V] = [DLF] \times [I] \qquad (15.b)$$

The solution for distribution system can be obtained by solving (16) iteratively.

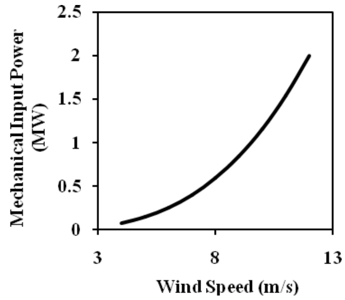
$$\left.\begin{aligned} I_i^k &= \left(\frac{P_i - jQ_i}{V_i^k}\right)^* + Y_i V_i^k \\ \left[\Delta V^{k+1}\right] &= [DLF]\left[I^k\right] \\ \left[V^{k+1}\right] &= \left[V^k\right] + \left[\Delta V^{k+1}\right] \end{aligned}\right\} \qquad (16)$$

4. RESULTS AND DISCUSSION

To order to analysis overall performance of MVDC offshore based WFDS, first Single PMSG based DC system is simulated and then simulation of overall WFDS having MVDC system is carried out in MATLAB independently. Here cut in and rated speed is taken as 4 m/s and 12 m/s.

4.1 Performance of single PMSG based DC System

A 2MW PMSG is considered as the basic generator for analysis and the details of the machine are given in the Appendix. Fig.5 (a) shows the input mechanical power. Since the power is directly proportional to the cube of wind, the input power increases with wind speed. In fig 5 (b) and (c) real power generated and efficiency is shown.



(a)

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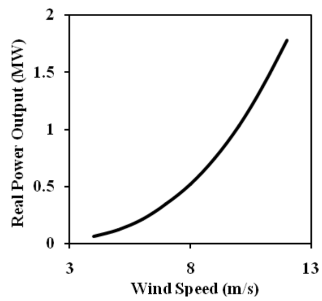
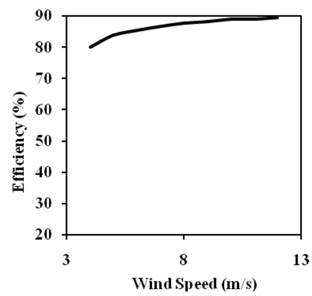


(b)



(c)

Fig. 5 (a) Mechanical Input Power ,(b) Real Power Output (c)Efficiency of PMSG based DC system

4.2 Performance of MVDC based WFDS

The voltage deviation at generator buses with to the local collection point voltage increases with increase in wind speed (Fig.6 (a)). Real power generated (Fig.6 (b)) increases with increase in wind speed and proportional to cube of the wind speed. Total losses, losses (%) and efficiency are shown in Fig.6 (c), 6 (d) and 6 (e) respectively.

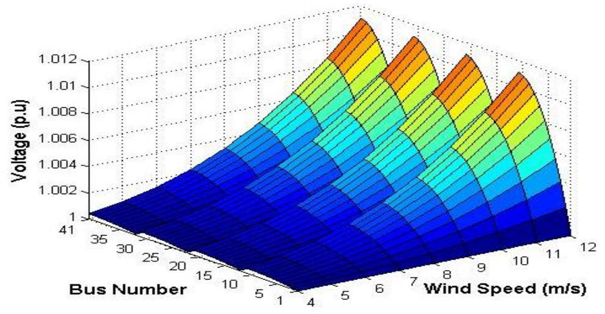
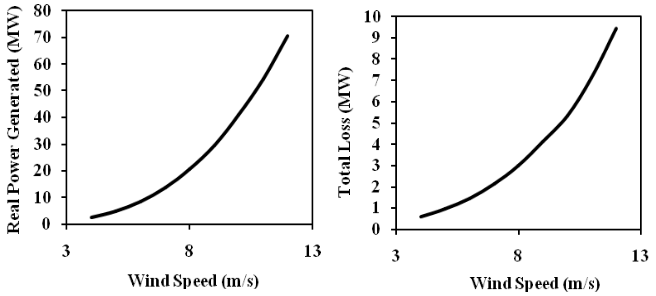
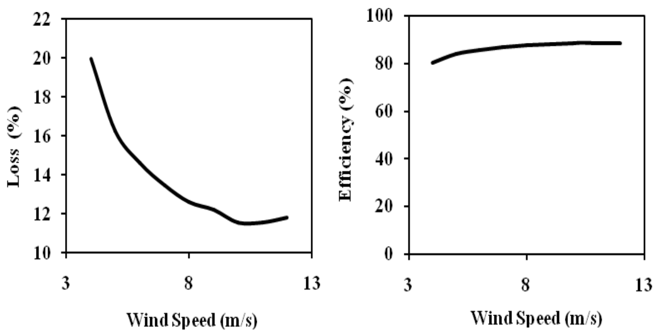


Fig. 6(a) Voltage Deviation in MVDC based WFDS



(b) (c)



(d) (e)

Fig.6 (b) Real power generated, (c) Total power loss,

(d)) Percentage Losses, (e) Efficiency in MVDC based WFDS

5. CONCLUSION

From the above results following conclusions can be drawn:

- Real power output is 72 MW
- Losses are 13% in MVDC system at rated wind speed (12 m/s).
- Efficiency is 80% in MVDC system at 4 m/s.

Appendix

Wind Turbine Specification	
Rating	2 MW
Radius	80 m
33 kV XLPE cable Parameters	
Resistance	0.0588 Ω/km (DC)
Converter Ratings	
AC-DC	2 MW
DC-DC	2 MW
PMSG Specification	
Rating	2 MW
Rated Speed	22.5 rpm
Rated Stator Voltage	690 V
No of Pole Pairs	26
Rated Rotor Flux	5.826 Wb
R_s (mΩ)	0.821
L_d (mH)	1.5731
L_q (mH)	1.5731

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