

Application of High Altitude Wind Power Generation as Distributed Generation and its Optimal Location and Sizing

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Abstract: *In conventional wind power generating systems the overall efficiency of the output power is less because of lower and unsteady wind speeds at lower heights. To overcome this drawback, the main parameter which has to be varied is the height at which the wind turbine has to be kept. To increase the height of the turbine, the tower height has to be increased for conventional wind turbines. This results in stability and cost constraints. This can be overcome by using High Altitude Wind Power. Here the energy is generated using the wind velocity at higher altitudes. In this paper, High Altitude Wind Power Generating system (HAWPGS) is applied in form of kite wind generator. Also, inclusion of HAWPGS as distributed generation and its optimal location in radial distribution network using voltage stability and loss Sensitivity indices is done. Also, the optimal size of the DG for all the buses are obtained in a IEEE 28 bus radial distribution network. The results are obtained using MATLAB programming.*

Keywords: Kite wind generator, distributed generation (DG), optimal location, loss sensitivity index, voltage sensitivity index, optimal size.

1. Introduction

The power demand in the present day is rapidly increasing. This is resulting in increasing pressure on the power utilities to supply more and more power to the ever increasing load demand. This has resulted in looking for new methods to generate power and supply the power while reducing power losses in distribution network.

One such method is to use distributed generation. In distributed generation, the power is generated at the location of load by either using renewable energy sources like solar panel, wind mill, etc. or non-renewable sources like diesel generators. As the power is being generated near the load, the distribution losses reduces considerably and the stress on the power utilities also reduces. DG also reduces environmental impact of power generation and improves system reliability.

Here high altitude wind power generation is used in the form of kite wind generator. First the output power for a kite wind generator with predefined operating parameters is calculated. Then the optimum location for the generating unit is obtained by sensitivity analysis and loss sensitivity indices after which the optimal sizes of the DG at each bus is obtained. This is done by using load flow calculation for a 28 bus IEEE distribution network. The resulting corresponding losses after placing optimal DG sizes at each bus are tabulated.

[1] presents simulation and experimental results regarding kite wind generators termed as ‘KiteGen’ using a

realistic kite model. In [1], nonlinear model predictive control is implemented using set membership approximation theory, to maximize energy from kitegen. [2] gives analytical modeling of pumping kite generator. In this paper, refined crosswind motion law is derived in case of equilibrium motion of the kite. [2] estimates mechanical power output of the pumping kite wind generator and gives a simple approximate formula for the mean mechanical power generated by the kite. This approximate formula is used in this paper to obtain the final power output from kite wind generator which is then given in to the distribution system in form of distributed generation.

[3] presents optimization studies for kite wind generation. The objective function is the average power at the generator. In [7], exact loss formula is used to find the optimum sizing of DG in each bus. This method gives accurate losses for corresponding DG sizes and takes less time for computation.

In this paper, the optimal sizes are obtained and optimal location is obtained based on those DG sizes, through the method in [7].

Here in section section 2, an introduction to High Altitude Wind Power generation is given. In section 3, power output from Kite Wind generator is obtained.in section 4 & 5, application of kite wind generator as DG is proposed and load flow for a 28 bus radial distribution network is carried out. In section 6,7 & 8, the optimal location and sizing of DG is carried out. In section 9, the results are tabulated. [2].

2. High Altitude Wind Power Generation

In high altitude wind power generation the generating unit is so designed to extract the power from wind flowing at higher altitudes. These technologies include airborne wind turbines and tethered airfoils. In airborne wind turbines, the generator along the turbine is made airborne thus the electric power is generated above and is sent to ground station through conductor cables. In case of tethered airfoils, which are also called kites, the wind energy is harnessed at high altitudes from which the mechanical energy is produced and transmitted to the ground station through tether. This mechanical energy rotates the rotor of generator located at ground station. Thus the electrical power is generated at ground only. Due to this construction, the system becomes simpler. But such simplicity is accompanied with complexity involved in controlling the kite position and length of the tether. There is also the need for rolling back the tether after it reaches certain maximum length due to limitation of tether length. This requires consumption of energy. But, a very large amount of power can be extracted from the kite wind generator than consumed while pulling back the tether, as the system operates at high altitude where the wind is flowing at higher velocities. Better designing of control mechanism for tether length and kite position helps minimizing power conversion losses and increase the power extraction thus making the system more efficient.

Many scenarios are suggested to extract power using kite wind generator. Out of them, two important modes are open-orbit or pumping mode, and the closed-orbit mode. In the former mode, the kite flies consequent lying eight orbits with increasing altitude until the tether reaches its maximum length, Hence the “recovery” phase starts and rolls the tether in and returns the kite to its initial position. In the “closed-orbit mode,” the kite is kept on a single eight shaped orbit, during which two regions are distinguished: a high and a low crosswind region. In the high crosswind region, the kite pulls out the tether which results in the traction phase, and in the low crosswind region, the tether is wound in, which accounts for the recovery phase.

3. Power output from Kite Wind Generator

In this work, a simplified expression for mean mechanical power output from a simple kite generating unit is considered from [2]. In this kite wind generator, the tether is rolled around a drum which is mechanically coupled with the generator. The kite under the force of wind gets a high lift and reaches higher altitudes. Under the effect of high speed wind the kite pulls the tether, thus it starts rotating the drum. This mechanical energy is transferred to the rotor of the generator. Once the kite reaches a certain maximum height and the tether certain maximum length, the tether needs to be pulled back and re-wounded around the drum. This requires consumption of energy and can be accomplished by using the same generator as a motor. The system is so designed that, minimum amount of energy is consumed while the kite is being pulled back. This is achieved by pulling the kite in such a way that its lift force is reduced considerably by suitable orientation of the kite. Such maneuvering is taken care of by the control mechanism employed for controlling the orientation of the kite in air. Once the tether is pulled back to certain length the operation of the electrical machine is switched to generator mode from motor mode resulting in electricity generation again. Such cycle including traction and retraction phases of the

kite continues and a net electrical power is produced, which is very high when compared to the power generation by conventional wind turbine generators.

Here a simple approximate formula for maximum mechanical power generated by kite wind generator is taken from [2] to get the maximum power output. The equation is given by

$$P_{Mmax} = \frac{1}{2} \rho_a A C_L V^3 (\cos v^*)^3 K_0 K^* \quad (2)$$

Where

$$K_0 = (4/27) G_e \sqrt{1 + G_e^2} \quad (3)$$

$$K^* = 1 - 2/3 (F_r^{gra} - W_c'') / (\rho_a A C_L K_0 V^2 (\cos v^*)^2) \quad (4)$$

Here v^* is the mean angle of inclination of the kite line with respect to the horizon.

$$v^* = \pi/2 - \theta^* \quad (5)$$

θ^* is the mean angle that the kite line forms with the vertical.

$$F_r^{gra} = mg \sin(v^*) \quad (6)$$

$$W_c'' = \mu g \sin(v^*) \quad (7)$$

Here

F_r^{gra} is the component of gravitational force.

W_c'' is the component of weight of the cable used.

G_e is the effective glide ratio of the kite and is obtained by using the relation from [3].

$$G_e = (C_L) / (C_D + \epsilon C_L^2 + (d r C_r) / (4 A)) \quad (8)$$

Here

V is the velocity of air.

C_r is the cable friction.

ϵ is the induced drag constant.

r is the length of the cable in meters.

d is the diameter of the cable in meters.

g is the acceleration due to gravity.

In W_c'' , the μ is the linear mass of the tether and is given by

$$\mu = \rho_t \pi d^2 / 4 \quad (9)$$

Here ρ_t is the linear density of the tether in Kg/m.

Based on these simplified expression, the kite power output P_{Mmax} is calculated. Here two phases of operation for the kite generating system are considered. One is traction phase, when the kite pulls the tether upwards causing generator operation. The other is retraction phase, when the tether is pulled back to initial length requiring motoring operation. Thus, in traction phase, the kite will produce mechanical power under the effect of high lift associated with the kite whereas, in retraction phase the kite will require mechanical power to be pulled back to initial height. This is made sure that, during retraction phase the mechanical power required for bringing back the kite to initial position is very less compared to power produced during traction phase. This is achieved by orienting the kite in such a position that its lift coefficient reduces significantly allowing the kite to be pulled back easily.

4. Application as DG

For considering kite power generation as distributed generation in a distribution network, an IEEE 28 bus radial distribution network is considered. Also the average electrical power output from kite generating system is considered with following assumptions.

The efficiency of the gearbox is assumed to be 95%. The efficiency of generator is assumed to be 90% and the

efficiency of the mechanical driving system is assumed to be 45% [2].

5. Load flow for distribution network

Here, for the 28 bus radial network BIBC, BCBV technique is used for load flow[6]. A brief explanation of this technique is as follows.

For a bus i, the complex power is given by

$$S_i = P_i + j Q_i = V_i I_i^* \tag{10}$$

Thus the corresponding equivalent current injection is given by

$$I_i = ((P_i + j Q_i) / V_i)^* \tag{11}$$

Here P_i and Q_i are active and reactive power specified in i^{th} bus. V_i is the voltage at the i^{th} bus. The branch current B is calculated with the help of BIBC matrix. The BIBC matrix is obtained from relation between bus current injections and the branch currents. The elements of BIBC matrix consists of ‘1’s and ‘0’s.

$$[B]_{nb \times X1} = [BIBC]_{nb \times (n-1)} [I]_{(n-1) \times X1} \tag{12}$$

Here nb is the number of branches in the system and n is the number of buses.

The bus voltages at different buses are obtained from the voltage at substation bus, branch currents and the branch impedance. Thus another matrix representing relation between drops in branch connecting substation bus to different buses and the impedances of the corresponding branches is formed and is given by

$$[\Delta V]_{nb \times X1} = [BCBV]_{(n-1) \times nb} [B]_{nb \times X1} \tag{13}$$

This expression can be written in terms of both BIBC and BCBV as

$$[\Delta V]_{nb \times X1} = [BCBV] [BIBC] [I] \tag{14}$$

These voltage drop values are then subtracted from the voltage value of the substation bus voltage to get the corresponding bus voltage value.

This process can be continued iteratively with proper convergence criteria to obtain the accurate voltage magnitudes at different buses. The results for this load flow problem are given in the tabular column.

5.1 Distribution networks

The data about the systems along the single line diagram are as given below with 100 MVA as base and first bus as substation bus.

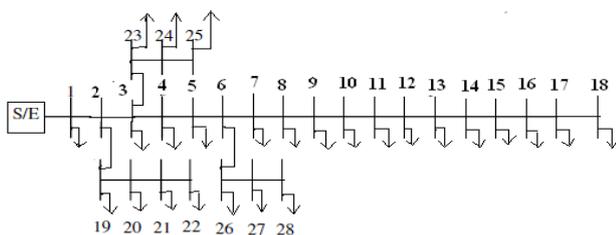


Figure 1: Single line diagram for IEEE 28-bus radial distribution network.

Table 1: The bus details for 28 bus radial distribution network

Sending Bus	Receiving Bus	R(Ω)	X(Ω)	P (KW)	Q (KW)
1	2	1.8216	0.7580	140	90
2	3	2.2270	0.9475	80	50
3	4	1.3662	0.5685	80	50
4	5	0.9180	0.3790	100	60
5	6	3.6432	1.5160	80	50
6	7	2.7324	1.1370	90	40
7	8	1.4573	0.6064	90	40
8	9	2.7324	1.1370	80	50
9	10	3.6432	1.5160	90	50
10	11	2.7520	0.7780	80	50
11	12	1.3760	0.3890	80	40
12	13	4.1280	1.1670	90	50
13	14	4.1280	0.8558	70	40
14	15	3.0272	0.7780	70	40
15	16	2.7520	1.1670	70	40
16	17	4.1280	0.7780	60	30
17	18	2.7520	0.7780	60	30
2	19	3.4400	0.9725	70	40
19	20	1.3760	0.3890	50	30
20	21	2.7520	0.7780	50	30
21	22	4.9536	1.4004	40	20
3	23	3.5776	1.0114	50	30
23	24	3.0272	0.8558	50	20
24	25	5.5040	1.5560	60	30
6	26	2.7520	0.7780	40	20
26	27	1.3760	0.3890	40	20
27	28	1.3760	0.3890	40	20

After finding out the power output of kite wind generator, the optimal location and Sizing of the kite wind generator is to be done. This is done using voltage stability index, loss sensitivity factors and the optimal sizing formula derived from exact loss formula as below.

6. Optimal location using Voltage Stability Index

From [7] , the bus stability index for Distribution networks is given as

$$SI(r) = 2V_1^2 V_2^2 - V_2^4 - 2V_2^2 (PR + QX) - |Z|^2 (P^2 + Q^2) \tag{15}$$

Here, V_1 and V_2 are the voltage at sending end and receiving end of a line respectively. P & Q are the real and reactive power sent through the line. R & X are the resistance and reactance of the line. This equation is used to find the stability index of each node. The node at which the value of stability index is minimum, is considered to be the most sensitive. The values of the stability indices are tabulated in the results.

7. Optimal location using loss sensitivity Index

The loss sensitivity index gives the indication that a bus is suitable for placing a DG. It is mainly used in DG allocation. For calculating the loss sensitivity index, the exact loss formula for real power loss is considered[7]. This is given by

$$P_L = \sum_{i=1}^N \sum_{j=1}^N [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - P_i Q_j)] \quad (16)$$

Where :

$$\alpha_{ij} = (r_{ij} \cos(\delta_i - \delta_j)) / V_i V_j \quad (17)$$

$$\beta_{ij} = (r_{ij} \sin(\delta_i - \delta_j)) / V_i V_j \quad (18)$$

The sensitivity factor of real power loss with respect to real power injection from DG is given by

$$\alpha_i = 2 \sum_{j=1}^N (\alpha_{ij} P_j - \beta_{ij} Q_j) \quad (19)$$

the buses are ranked in descending order of their values of sensitivity factors. The buses with high values of sensitivity factor are first studied for DG location.

8. DG Sizing

The optimum DG sizes can be determined by using the real power loss sensitivity factors[7]. At minimum losses, the rate of change of losses with respect to injected power becomes zero.

$$\sum_{j=1}^N (\alpha_{ij} P_j - \beta_{ij} Q_j) = 0 \quad (20)$$

$$P_{DG_i} = P_{D_i} + [\beta_{ii} Q_i - \sum_{j=1, j \neq i}^N (\alpha_{ij} P_j - \beta_{ij} Q_j)] / \alpha_{ii} \quad (21)$$

Here P_{DG_i} = real power injection from DG placed at node i

P_{D_i} = load demand at node i .

DG size other than the values obtained by above relation will lead to higher losses.

9. Results

The maximum mechanical power for given parameters of a kite wind generator is obtained as 4.3179 MW. Thus the electrical power is obtained as $P_e = 0.9 * 0.95 * 0.45 * P_m = 1.6613$ Mw.

After finding the voltage stability indices, the most sensitive bus in the network is obtained as Bus number 18 which is having the lowest value.

From the plots of the voltage stability indices it is clear that 18th bus is the most sensitive bus to voltage instability. Here the total loss and total real and reactive powers are as given in table.

From the values of voltage stability indices bus no. 18 is having the lowest value. From the loss sensitivity values the bus no. 13 is having highest value resulting in first preference for placing the DG.

As per the optimal sizing formula, the DG optimal sizes at each bus and the corresponding losses in the system when the optimal sizes of the DG are placed at respective buses are tabulated. The bus at which, when the optimum size of the DG is placed, results in minimum total loss in the

system, is considered to be the optimal location of the DG having optimal size. This optimal location is based on minimization of system losses.

Table 2: Total power loss, Total Real & Reactive Power

Total loss in network=P(loss)	108.03 KW
Total real Power = P(total)	1.9000 MW
Total reactive Power = Q(total)	1.0700 MVAR

As per the values of losses, bus no. 11 is having minimum loss value when its optimum size DG is placed at it. Thus bus no. 11 is the optimum location of DG in terms of loss minimization.

The loss in the system, when optimal size of the DG is placed at each bus is plotted as below.

10. Conclusion

From the results obtained after running the load flow with sensitivity analysis and observing the voltage magnitudes it can be concluded that High altitude wind power generation can be used as distribution generation in distribution network to satisfy the increasing load on the system.

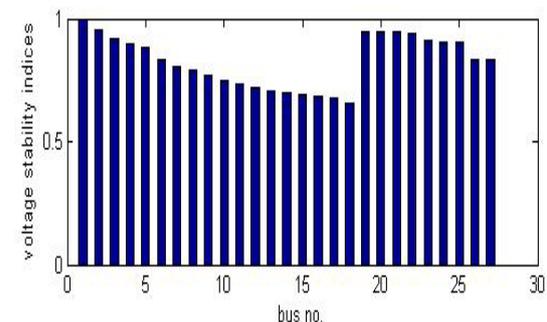
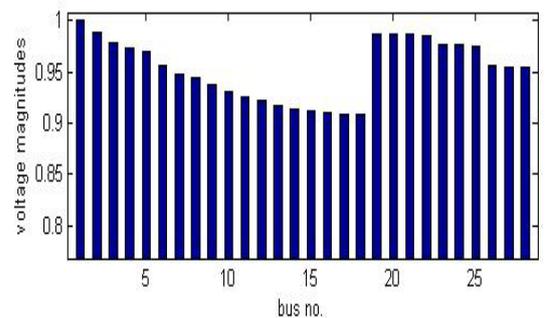


Figure 2: Voltage magnitudes and voltage sensitivity indices at each bus

Table 3: Voltage magnitudes with Index values

Bus no.	Voltage magnitude	Voltage stability indices	Loss sensitivity factor
1	1.0000	0.9980	-
2	0.9892	0.9560	0.0350
3	0.9783	0.9153	0.0406
4	0.9727	0.8945	0.0512
5	0.9691	0.8798	0.0725
6	0.9561	0.8341	0.0839
7	0.9480	0.8070	0.1114
8	0.9441	0.7932	0.1199
9	0.9375	0.7707	0.1194
10	0.9297	0.7458	0.1522
11	0.9248	0.7310	0.1460
12	0.9227	0.7231	0.1508
13	0.9175	0.7072	0.1835
14	0.9135	0.6953	0.1518
15	0.9111	0.6882	0.1572
16	0.9094	0.6829	0.1608
17	0.9080	0.6790	0.1409
18	0.9075	0.6541	0.1420
19	0.9872	0.9493	0.0223
20	0.9866	0.9468	0.0170
21	0.9859	0.9438	0.0183
22	0.9854	0.9415	0.0157
23	0.9767	0.9093	0.0281
24	0.9758	0.9049	0.0297
25	0.9749	0.9012	0.0373
26	0.9552	0.8321	0.0437
27	0.9548	0.8310	0.0443
28	0.9547	-	0.0446

12	0.8247	39.5917
13	0.7188	41.7408
14	0.6837	43.0163
15	0.6340	45.2085
16	0.5911	47.6269
17	0.5510	51.0450
18	0.5138	53.9476
19	0.6830	98.8215
20	0.5810	100.0112
21	0.4074	101.8686
22	0.2658	103.7337
23	0.9138	86.7504
24	0.6562	91.6199
25	0.3985	96.8069
26	1.0632	61.1596
27	0.9591	65.0075
28	0.8701	68.4748

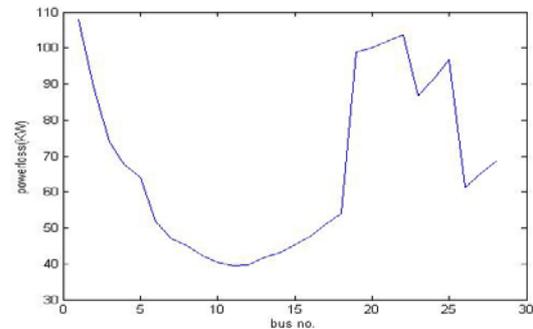


Figure 3: Plot of Powerloss vs Bus no.

If Kite power generation is applied in form of high altitude wind power generation then it is possible to produce more power at less initial cost at same site with same wind conditions when compared to conventional wind turbines. It is also concluded that when distributed generation is located at the most sensitive bus, the voltage profile improves indicating less stress on the power generation. Also placement of optimal DG size at Optimal location in terms of loss minimization results in minimum power loss in the system.

Table 4: Optimal Sizes with losses

Bus no.	Optimum Sizes(MW)	Corresponding losses(KW)
2	1.7050	89.2307
3	1.6113	73.7739
4	1.5010	67.4816
5	1.4005	64.1380
6	1.2670	51.9623
7	1.1358	47.0464
8	1.0840	45.0498
9	1.0158	42.2302
10	0.8993	40.4729
11	0.8556	39.4395

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