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Maximizing Wind Power Integration in Distribution System

S. Nursebo Salih, P. Chen, O. Carlson

Abstract-- Due to the location of favorable wind sites and lower connection costs associated with installing wind power in a distribution system, there is a need to know the hosting capacity of a distribution system so that it can be used effectively for injecting wind power into the power system. Therefore this paper presents a methodology to investigate the wind power hosting capacity of a distribution system. Stochastic nature of wind power and customer loads is taken into account using copulas. Hence it is possible to investigate various levels of correlation among customer loads. A simple algorithm is proposed for selecting the connection points of wind power in the network. The effectiveness of active management strategies such as wind power curtailment and reactive power compensation are thoroughly investigated. The analysis shows that allowing a curtailment level of as low as 0.2% with power factor (PF) control of wind turbines could boost the hosting capacity by 118%.

Index Terms—Monte Carlo simulation, Copula, active management strategy, multi period optimal power flow

I. INTRODUCTION

Distribution systems (DSs) are favored when connecting wind turbines/farms to the grid for two main reasons. First, the connection cost is lower than the transmission system. Second, favorable wind sites are usually located away from the transmission grid. But the wind power hosting capacity of DSs is limited by power quality problems that wind power imposes to customer loads. Hence various researches are done on optimal sizing and siting of wind power or distributed generation (DG) in general in DSs. Optimal power flow (OPF) based approach is proposed to determine the available headroom for DG [1] and wind power [2] in a DS. Genetic algorithm (GA) [3], [4], and combined OPF and GA [5], [6] are used to determine the optimal position and size of DGs. In [7], multi period OPF is used to determine the maximum wind energy hosting capacity of DSs.

Moreover active management strategies such as wind power curtailment [2], [7], [8], reactive power compensation [8], voltage control using coordinated on load tap changer [2], [7], [8], and power factor (PF) control of wind turbines [7] are investigated to increase the DG or wind power hosting capacity of DSs.

System load and wind power are also modeled in different details. In most papers [1], [3]-[6] single loading level of customer loads is considered. But customer loads and wind power are variable in nature. Hence this approach does not provide sufficient information about hosting capacity of the distribution networks. In [8], one year customer load data is used. However, one year load data for each customer node is rarely available and is cumbersome to work with. In [2], [7] Clustering techniques are used based on load duration curve and cumulative distribution function or measurement data; where full correlation is assumed among loads and wind power at different buses. Though the approach captures the stochastic nature of wind power and load data to some level, it lacks flexibility to model load data with different correlation levels. Moreover it is known that customer loads are not fully correlated though they could be highly correlated.

Hence, this paper presents a more realistic modeling of load and wind power based on copulas. This gives greater flexibility in analyzing the wind power hosting capacity of DSs. Hence a thorough analysis is provided to evaluate wind power hosting capacity and the effectiveness of different active management strategies in increasing this hosting capacity in a DS. The overall optimization procedure is solved using multi period optimal power flow which is implemented using GAMS optimization software.

II. LOAD AND WIND DATA MODELING BASED ON COPULAS

Customer loads and wind power has stochastic nature which can be modeled using probability density functions (PDFs) and cumulative distribution function (CDFs). Once they are modeled, a synthetic data can be generated using the model which is then used for analysis. A parametric or non-parametric model can be used to represent their PDF. But the problem is how to represent their CDF. Using copula to model the CDF of loads at different buses and wind power at different sites has been proposed in [9]; the same modeling approach is followed in this paper.

A. Copula

Given p random variables x_1, x_2, \dots, x_p with corresponding marginal distribution $F_1(x_1), F_2(x_2), \dots, F_p(x_p)$, their multivariate distribution function can be given by [10]

$$F(x_1, x_2, \dots, x_p) = C[F_1(x_1), F_2(x_2), \dots, F_p(x_p)] \quad (1)$$

where C is the copula. Here one should note that the marginal functions $F_1(x_1), F_2(x_2), \dots, F_p(x_p)$ can assume

This work was financed by Chalmers energy initiative.

S. Nursebo Salih is with Chalmers University of Technology, Sweden (email: Shemsedin.nursebo@chalmers.se)

P. Chen is with Chalmers University of Technology, Sweden (email: peiyuan@chalmers.se)

O. Carlson is with Chalmers University of Technology, Sweden (email: Ola.carlson@chalmers.se)

any distribution independent of each other and the copula structure.

There are a number of families of copulas which have different capabilities in dependence modeling and have their own pros and cons. The most common families of copulas are elliptical copulas and Archimedean copulas [10], [11]. But due to greater flexibility of Gaussian copula to model dependence, Gaussian copula is chosen here. Gaussian copula belongs to the family of elliptical copulas.

B. Multivariate Gaussian Copula

Define ρ as symmetric, positive definite matrix with diagonal elements equal to 1. Φ_ρ is the standardized multivariate normal distribution with correlation matrix ρ . Then the multivariate Gaussian copula is defined as [16]:

$$C(u_1, u_2, \dots, u_p; \rho) = \Phi_\rho[\Phi^{-1}(u_1), \Phi^{-1}(u_2), \dots, \Phi^{-1}(u_p)] \quad (2)$$

The corresponding density is

$$C(u_1, u_2, \dots, u_p; \rho) = \frac{1}{|\rho|^{1/2}} \exp\left(-\frac{1}{2}\zeta^T(\rho^{-1} - \mathbb{I})\zeta\right) \quad (3)$$

where $\zeta_n = \Phi^{-1}(u_n)$ and u_1, u_2, \dots, u_p are uniform random variables.

The simulation technique using Gaussian copula can be found in [11].

III. SELECTION OF WIND TURBINE CONNECTION POINTS

As it is noticed by various researchers the limiting factor in installing more wind power in a radial distribution system is the voltage rise problem [1], [8]. For such case it is noticed that those buses near the substation can host more wind power. Besides, once a given bus has hosted the maximum wind power then those buses downstream no longer host any substantial power. One can prove this by using a voltage sensitivity analysis. Hence, in this work, among the available candidate sites those sites near the substation are chosen. Furthermore, only one site per feeder or lateral is selected. The procedure is illustrated in fig. 1.

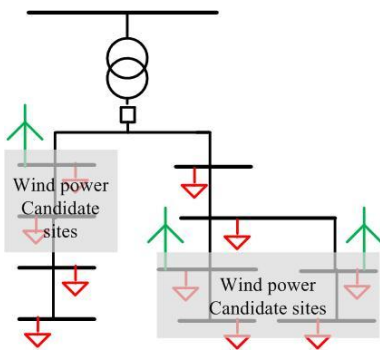


Fig. 1. Siting wind turbines (assume that we need to choose three sites from available six candidate sites. Then the selection will be as shown in this fig)

IV. PROBLEM FORMULATION

The problem considered here is maximizing the wind power hosting capacity of a DS. Hence the objective function is:

$$\max O(P_i) = \sum_{t \in T} \sum_{i \in I} P_{i,t} \quad (4)$$

where $P_{i,t}$ is the wind power injected at bus i and time t . I and T are sets containing all selected wind sites and generated samples respectively.

To prevent the optimization procedure from increasing the penetration by increasing the loss in the system, the loss equation is included in the objective function as follows.

$$Loss = \frac{1}{2} \sum_{i \in B} \sum_{j \in B} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_j - \delta_i)) \quad (5)$$

$$\max O(P_i) = \sum_{t \in T} \sum_{i \in I} P_{i,t} - loss \quad (6)$$

where j is another index for buses, G_{ij} is the conductance of the line $i-j$, V_i is the voltage level at bus i , δ_i is the voltage angle at bus i , B is a set containing all buses in the system.

There are also equality and inequality constraints involved in the optimization procedure. The equality constraints include the load flow equations:

$$P_{i,t} - PD_{i,t} = \sum_{j \in B} Y_{ij} V_{i,t} V_{j,t} \cos(\theta_{ij} + \delta_{j,t} - \delta_{i,t}) \quad (7)$$

$$Q_{i,t} - QD_{i,t} = -\sum_{j \in B} Y_{ij} V_{i,t} V_{j,t} \sin(\theta_{ij} + \delta_{j,t} - \delta_{i,t}) \quad (8)$$

where $P_{i,t}$ and $Q_{i,t}$ are the injected active and reactive power at bus i and time t , $PD_{i,t}$ and $QD_{i,t}$ are active and reactive power demand at bus i and time t , Y_{ij} and θ_{ij} are the magnitude and angle of admittance of the line $i-j$ respectively.

The inequality constraints considered are

- The bus voltage limit

$$V_{min} \leq V_{i,t} \leq V_{max}, \forall i \in B, \forall t \in T \quad (9)$$

The limit taken in this paper is $\pm 5\%$ of the nominal value.

- The limit on the ampacity of the cable

$$Y_{ij}^2 \{V_{i,t}^2 + V_{j,t}^2 - 2V_{i,t} V_{j,t} \cos(\delta_{i,t} - \delta_{j,t})\} < I_{ij}^2 \quad \forall Y_{ij} > 0 \quad (10)$$

where I_{ij} is the ampacity of the line $i-j$.

- Limit on the available active and reactive power

$$Q_{mn_i} \leq Q_i \leq Q_{mx_i} \quad (11)$$

$$P_i \leq P_{mx_i} \quad (12)$$

where Q_{mn_i} and Q_{mx_i} are the minimum and maximum reactive power and P_{mx_i} is the maximum active power available at bus i for injection.

- The limit on transformer rating or limit imposed by the external grid owner at slack bus (sb), S_{lim}

$$P_{sb,t}^2 + Q_{sb,t}^2 \leq S_{lim}^2 \quad \forall t \in T \quad (13)$$

where $P_{sb,t}$ and $Q_{sb,t}$ are the active and reactive power flows through the transformer at time t .

- The limits on transformer tap setting

$$a_{min} \leq a_t \leq a_{max} \quad \forall t \in T \quad (14)$$

where a_t is the tap position of the transformer.

- The limit on curtailed wind energy

$$\sum_{t \in T} \sum_{i \in I} (ng_i * WP_{av_{i,t}} - P_{i,t}) < crpr * \sum_{t \in T} \sum_{i \in I} ng_i * WP_{av_{i,t}}, \quad \forall t \in T, i \in I \quad (15)$$

where $WP_{av,t}$ is the per unit wind power available at bus i and time t , ng_i is the peak value of the installed power, and $crpr$ is the level of curtailment in percentage.

V. A CASE STUDY

The proposed approach is tested on the widely studied 69-bus distribution network [2]. As mentioned in section II, the load and wind samples are generated using Monte Carlo simulation based on copula. In the simulation, wind power at different sites is assumed to be completely independent of the loads in the system but fully correlated within themselves. Different levels of correlation between the loads in the system are used to investigate its effect on wind power hosting capacity of the DS. These include:

1. Full correlation between all loads (designated as “ $\rho=1$ ” below), with minimum load of 0.00MVA and maximum load of 11.64 MVA
2. A correlation coefficient of $\rho\approx 0.88$ between all loads (designated as “ $\rho=0.88$ ” below), with minimum load of 1.15MVA and maximum load of 11.06MVA
3. A correlation coefficient of $\rho\approx 0.59$ between all loads (designated as “ $\rho=0.59$ ” below), with minimum load of 0.28MVA and maximum load 10.89MVA
4. Different levels of correlation¹ among the loads in the system (designated as “diff ρ ” below), with minimum load of 1.24MVA and maximum load of 10.56 MVA

In selecting candidate buses, the first assumption is that the following buses are candidate sites for wind power installation: [7-9,11-15,20-22,28,29,33-49,54-56,59,60,61-69]. Next it is assumed that all buses, except the slack bus, are available for wind power installation. Hence the investigation is carried out for both cases. Following the procedure in section III the following buses are selected:

- Group1 wind farms (G1): [33,39,54,59,7,11,20,28]
- Group2 wind farms (G2): [2, 16, 30, 51], where Each wind farm has a capacity factor of 33.4%.

VI. RESULTS AND DISCUSSION

A. Hosting Capacity, Active Management Strategy and Correlation among Loads

Fig.2 shows the wind power hosting capacity of the studied distribution network for different correlation levels among the loads as well as for different active management strategies. In the analysis for curtailed energy, the following curtailment levels are considered: for G1 the curtailment level is below 0.2% and for G2 it is below 0.06%.

The difference in penetration due to different levels of correlation between the loads is not substantial. However the hosting capacity analyzed based on the full correlation among the loads always tends to be the lowest. This is because more correlated loads tend to have lower minimum loading condition. Hence the hosting capacity of the DS will be lower.

On the other hand, particularly, for G1 the penetration level varies substantially for different active management

strategies, the highest being for RC & CE case, see fig 2. Moreover, as compared to G1, G2 does not show any significant increase in penetration due to reactive power compensation. This is because the penetration for these wind farms is not limited due to constraints on bus voltages. Instead it is limited due to thermal capacity of the transformer. And replacing the reactive power flowing through the transformer with reactive support in the substation does not result in substantial increase in hosting capacity. Hence for these wind farms CE is more effective.

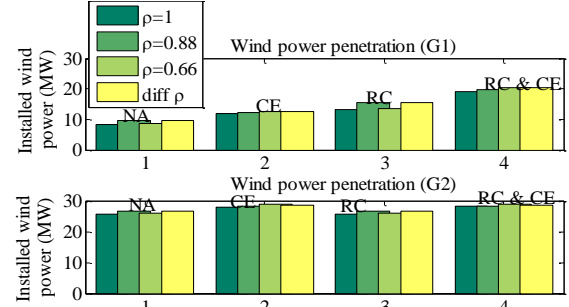


Fig. 2. wind power penetration and for different active management strategies and different correlation levels among the loads (NA represents no active management strategy, CE represents wind power curtailment, RC represents reactive power compensation which includes PF control of wind turbines, RC&CE represents both wind power curtailment and reactive power compensation)

B. Reactive Power Compensation

Here the wind turbines are operated to consume reactive power when the voltage limit at the terminals of the turbines is violated. Depending on the grid situation and the transformer capacity this may demand for extra reactive power compensation device at the substation. For G1, the reactive power demand by the wind turbines is effectively taken care of by the grid for all cases. Fig.3 shows the extra reactive power demand from the grid relative to the base case² for G1 for RC case.

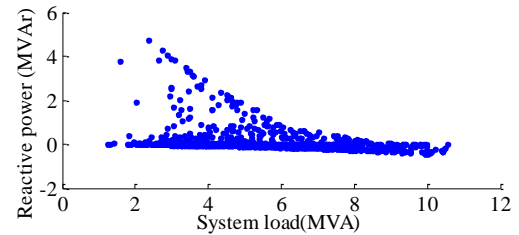


Fig. 3. Extra reactive power consumption from the grid compared to the reactive power consumption at the base case (diff ρ and RC)

It can be seen that more reactive power is demanded at low loading than the base case but the demand is lower at high loading. This is because at low loading wind turbines consume reactive power to avoid voltage limit violation. But, at high loading, since the turbines are closer to the loads than the substation they reduce the reactive power consumed by the cables and hence the overall reactive power. This has the advantage to lower the voltage on the transmission system at low loading condition and reduce the reactive power demand at high loading condition. On the other hand for RC & CE case (see fig.4) the reactive power demand increases relative to the base case. This is because

¹ This correlation varies between ≈ 0.44 and 0.91

² Here the base case is the case where no wind power is installed

the power generation from the wind turbines is higher than the RC case and the wind farms, in this case, need to consume reactive power at all loading conditions to avoid voltage limit violation. However this reactive power consumption is not at all times but it is only when the wind power generation is relatively higher than the load.

C. Wind Power and Stress on the Transformer

In this work, for G1, except for RC & CE case, the stress on the transformer is reduced. Fig.5 shows the frequency distribution of stress on transformer for the base case and the NA case. From the figure it can be seen that for the NA case, compared to the base case, higher power through the transformer is less common, which means that the transformer is less stressed. This will have a positive impact on the life time of the transformer.

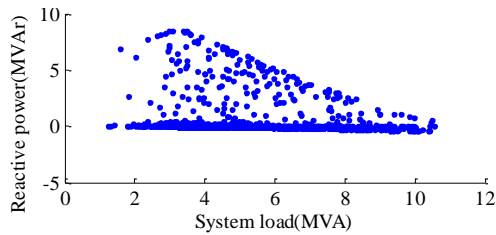


Fig. 4. Extra reactive power requirement due to Wind power (diff p and RC&CE)

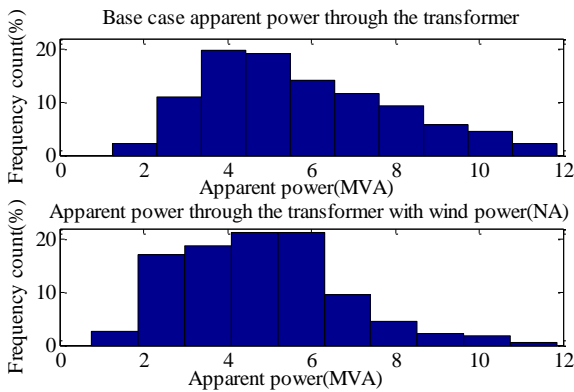


Fig. 5. wind power and stress on the transformer

VII. CONCLUSION

This paper investigates the maximum power installation in a DS. The paper uses copula to model the stochastic nature of wind power and load in a DS. This has given great flexibility to represent load and wind power in the system. Hence the paper has used different levels of correlation between the loads to investigate its effect on the hosting capacity of the system. For the case studied the hosting capacity of the system shows some variation depending on how correlated the loads on the system are; in general the more correlated the loads are the lower the hosting capacity of the system. Moreover the paper analyzes how active management strategies can be used to increase the hosting capacity of a DS. In general the maximum hosting capacity will be achieved when both reactive power compensation and wind power curtailment are used. The case studied here shows that even with as low level of curtailment as 0.2% and using PF control of wind turbines the penetration could be boosted by almost 118%. This however depends on how the wind farms are electrically far from the substation.

Moreover the case studied here shows that introducing reactive compensation can even provide better stability to the voltage of the power system. It is also observed that introducing wind power can lead to lower stress on the transformer which contributes to longer life of the transformer.

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IX. BIOGRAPHIES

S. Nursebo Salih was born on March 10, 1983 in Ethiopia. He studied his B.Sc. in electrical engineering at Arba Minch University, Ethiopia. He did his M.Sc. in power engineering at Chalmers university of Technology, Sweden, from where he graduated in 2010. Now he is doing his PhD degree at Chalmers University of technology. His research area is wind power integration in distribution system.

Peiyuan Chen (S'2007, M'2010) received his B.Eng. degree in Electrical Engineering from Zhejiang University, China, in 2004, M.Sc. degree in Electric Power Engineering from Chalmers University of Technology, Sweden, in 2006, and PhD degree in Stochastic Modelling and Analysis of Power System with Renewable Generation from Aalborg University, Denmark, in 2010. Currently, he is assistant professor at both Aalborg University and Chalmers University of Technology. His main research interests are optimal operation and planning of power system with integration of wind power.

Ola Carlson was born in Onsala, Sweden in 1955. He received the M.Sc. and Ph.D. degree in Electrical Engineering from Chalmers University of Technology, Gothenburg, Sweden in 1980 and 1988, respectively. He is currently an Associate Professor at the Department of Energy and Environment at Chalmers University of Technology. He had three years of industry experience in the areas of variable speed systems for wind turbines. His major interests are electrical systems for renewable energy and hybrid electric vehicles.