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Impact of power fluctuations in reactive power capability of wind power plants

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SUMMARY

Due to characteristics of wind which is inherently variable, active power production from wind power plants fluctuates over time. Reactive power capability of wind power plant is dependent on active power production. This paper investigates the impact of active power fluctuations on reactive power capability of wind power plants and quantifies the impact. For this purpose time series data of active power production with fluctuations from aggregated wind power plant is simulated. This time series is then used to calculate reactive power capability time series of the aggregated wind power plant. Different time periods have been used for calculating mean values of reactive power capability. Then, ramp rates has been calculated to quantify mean value changes between two consecutive time periods. From the case study performed, it is observed that active power fluctuation has an impact on reactive power capability - increasing the averaging time period increases the ramp rate of reactive power capability.

KEYWORDS

power fluctuation, reactive power capability, ramp rate, long-term voltage stability, time series analysis, long-term power system studies

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1 INTRODUCTION

According to International Energy Agency, wind power will be leading source of electricity in EU by 2030 [1]. There is increase in both onshore and offshore wind. Adequate locations suitable for wind power production are moving further away from transmission grids, for both onshore and offshore. These wind power plants (WPP) are connected to the transmission grid through long AC cables. Presently, large WPPs like Anholt (399.6 MW) and Horns Rev 2 (209.3 MW) are located at distances 15 km and 31.7 km from shore respectively [2]. Future WPP projects of larger installed capacity will be situated further away from the shore [3]. For example, Hornsea Project One which is under construction phase, is a 1.2 GW offshore WPP located 120 km off Yorkshire coast in the UK [4].

Due to increasing cost of fossil fuels, reducing prices of wind and solar power technology, and growing concerns for environment and energy security, synchronous conventional generators are being replaced by converter connected non-synchronous generators. As a result, traditional reactive power sources are reducing in the power system. Therefore, reactive power support from large WPPs will be crucial in future power systems with large share of renewable generation sources (RES). Moreover, long transmission lines connecting large WPPs to the transmission grid makes the power system weaker due to low short circuit ratio (SCR). In such cases, reactive compensation may be required to maintain nominal voltages in the system. In future converter dominated power systems, reactive power capability of wind power plants (WPP) can be essentially useful for enhancing voltage quality and stability of the grid.

In literature, there are numerous applications of reactive power capability of WPPs, both for voltage control and for voltage stability studies. Centralised voltage control of WPPs utilising reactive power capability of WPPs has been studied by Kim et. al. in [5]. To analyse reactive power support from wind to improve grid voltage performance, Yagnik et. al. [6] investigated voltage control mode of WPPs modelled with reactive power capability of WTs. Karbouj and Rather [7] proposed a centralised voltage control of WPP so as to supply dynamic reactive power from WPP. For this purpose reactive power capability curves of WT has been used.

Reactive power capabilities of WTs and WPPs have also been used for voltage stability studies. Meegahapola et. al. [8] utilised reactive power capability curves for dynamic voltage stability studies. Long-term voltage stability studies applying reactive power capability curves were performed by Londero et. al. [9] and Amarasekara et. al. [10]. Furthermore, voltage stability assessment method for transmission network with high penetration of wind power has been developed by [11] which includes reactive power capability of WTs.

Computation of reactive power capability curves are crucial. Maximum reactive power capability of WPP is dependent on wind power collection grid parameters and transmission grid side voltage. As for modern Type 4 WTs [12,13], reactive power generation is dependent on grid side converter (GSC). GSC parameters (like MVA rating, maximum current rating, maximum and minimum allowable converter voltages) as well as active power production from WTs determine maximum reactive power capability of individual WTs.

Active power production is dependent on characteristics of wind which is inherently variable in nature. Variability of wind causes fluctuation in active power production of WPPs as shown by Sørensen et. al. in [14]. The motivation for this paper is to see if reactive power capability of
WPP is affected by active power fluctuation. Provided that active power fluctuations impacts reactive power capability, this work will investigate how it is affected and quantify the impact.

2 MODELLING

Voltage source converters (VSCs) are capable of controlling active and reactive power generation independently. However, maximum apparent power generation are limited by converter size and rating. Therefore, reactive power output from converters vary according to available active power depending on wind speed. Due to the stochastic nature of wind, assuming mean wind speed does not give realistic reactive power capability of WPPs. Using reanalysis time series directly can underestimate the short-term wind variability [15]. To obtain realistic simulations, stochastic fluctuations can be added to reanalysis wind speed data [16], which results in fluctuations in available active power and consequently affect reactive power availability. Analysing the short-term variability in more detail can support power system, especially during stressed system conditions when maximum reactive power support from WPPs is needed. Methodology followed in this work is illustrated in Fig. 1.

2.1 Active Power Fluctuation

Larsén et. al. [15] have shown that, wind simulated from meteorological mesoscale weather models are underestimated with respect to short-term variations in wind. Therefore, in order to obtain realistic simulations, wind speed fluctuations are simulated as stochastic time series and added to wind speed output of mesoscale weather models. The fluctuation model used, is based on work done by Sørensen et. al. in [17]. Correlations in Renewable Energy Sources (CorRES) [16], is a tool developed at Technical University of Denmark, Department of Wind Energy, that combines both meteorological data and stochastic simulations, to generate wind speed/power time series. For this paper, the time series obtained from CorRES are aggregated at WPP level and at a resolution of one minute.

2.2 Reactive Power Capability

Reactive power capability curve for Type 4 WTs is modelled based on methodology proposed by Ullah et. al. in [18]. To aggregate the WPP, output of a single WT is scaled up according to number of WTs in the WPP. Also, the impedance of WT transformer is multiplied by the total number of WTs to get equivalent impedance of all WT transformers in the WPP. This methodology has been used by Ullah et. al. in [18]. Collector grid losses are neglected in this method. According to [18], converter current limited reactive power and converter voltage limited reactive power are given by equations 1 and 2 respectively.

\[ Q_c = \sqrt{(V_g^2)_{c,max}} - P^2 \]  

Figure 1: Block diagram of methodology
\[ Q_v = \sqrt{\left(\frac{V_{c,max}V_g}{X}\right)^2 - P^2 - \frac{V_g^2}{X}} \]  

(2)

where,

- \( Q_c \) = converter current limited reactive power
- \( Q_v \) = converter voltage limited reactive power
- \( V_g \) = voltage at the grid connection point
- \( P \) = active power production from WPP
- \( X \) = aggregated impedance of all WT transformers
- \( I_{c,max} \) = maximum converter current
- \( V_{c,max} \) = maximum converter voltage

From [1] and [2], maximum reactive power capability from WPP at any instance is calculated as,

\[ Q = \min\{Q_c, Q_v\} \]  

(3)

3 CASE STUDY

Using the methodology described in the above section, simulations are done for Horns Rev 2, 210 MW WPP. Fig. 2 shows the layout of Horns Rev 2 WPP. (Dots represent individual WTs and the black square represents the WPP transformer. Dotted lines represent 33kV collection grid cables.) One year time series of active power is simulated for the Horns Rev 2 location to calculate reactive power capability time series of the aggregated WPP. For these studies, it is assumed that the grid voltage is equal to 1 p.u., and the grid code requirements and capability curve modelled with respect to this voltage. This assumption is valid since large WPPs are generally connected to the grid through on-load tap changing transformer responsible to maintain the voltage at the low voltage end.

Maximum converter current, \( I_{c,max} \) is designed to be 1.25 p.u. with reference to the WT generator capability curve presented in [19]. Maximum converter voltage, \( V_{c,max} \) is taken as 1.1 p.u. while minimum converter voltage, \( V_{c,min} \) is taken as 0.8 p.u. With these design values, reactive power capability of aggregated Horns Rev 2 power plant is obtained. It is shown in red colour in Fig. 3 Danish grid code [20] requirement for connection to grid at the point of connection, for nominal voltage level is shown in black in Fig. 3. It can be observed that, grid code requirement
In this paper, ramp rate of reactive power is evaluated similar to active power ramp rate studied by Sørensen et. al. in [14]. According to definition of ramp rate defined by Parson et. al. in [21], ramp rate can be defined for a time period which reflects the time scale of interest. To study long-term time horizon based studies, ramp rate of maximum reactive power capability with larger time period is of interest. Whereas, for short-term time horizon based studies, ramp rates with shorter time period is of interest. Therefore in this paper, different time scales - 1-min, 10-min and 30-min - averaging time periods are chosen to study effect of active power fluctuation (due to variability of wind) on reactive power capability. As GSCs can both inject as well as absorb reactive power from the grid, reactive power capability of WPP can be determined for both injection and absorption which are not symmetrical in nature. For the case study done in this paper only injection capability of reactive power is studied. Henceforth, the term ‘reactive power capability’ will imply capability of WPPs to inject reactive power into the grid.

3.1 Ramp Rate of Reactive Power Capability

Reactive power capability ramp rates adapted from the definition of active power ramp rate by Parson et. al. in [21] and Sørensen et. al. in [14] is given in equation \(4\). Ramp rate quantifies the change in mean value between two consecutive time periods.

\[
Q_{\text{ramp}} = Q_{\text{mean}}(n + 1) - Q_{\text{mean}}(n)
\]

where,

- \(Q_{\text{ramp}}\) = ramp rate of reactive power capability
- \(n\) = time period
- \(Q_{\text{mean}}\) = mean value of reactive power capability for each time period

Instantaneous and 30-min mean value of reactive power capability are shown in Fig. 4. Reactive power capability ramp rates are shown with black arrows in Fig. 4. The instantaneous value of reactive power capability is simulated using the active power time series, at a resolution of 1-min time step. The mean value of reactive power capability is calculated at the end
Figure 4: Illustration of ramp rate definition for time period of 30-min

of each 30-min time period. Then using the definition of reactive power capability ramp rate from equation (4), reactive power capability ramp rate is calculated as change in mean value between two consecutive time periods. Positive reactive power capability ramp rate signifies increase in reactive power capability whereas negative ramp rate denotes decrease in reactive power capability.

Using the above mentioned procedure, reactive power capability ramp rates are calculated for time periods of 1-min, 10-min and 30-min. Since the data set used for this paper is at a resolution of 1-min, reactive power capability ramp rate for 1-min time period is essentially the difference between two consecutive data points. Using these reactive power capability ramp rate series, duration curve is obtained for each averaging time-period.

Fig. 5 shows the duration plot obtained for 1-min, 10-min and 30-min time periods. Duration curve of 30-min reactive power capability ramp rates show higher positive as well as negative ramping when compared to 1-min reactive power capability ramp rates. This is as expected because, there is less variability of wind in short-term duration (1-min) than in long-term duration (30-min). High positive reactive power capability ramping signifies that reactive power capability is increasing fast, whereas, high negative reactive power capability ramping signifies that reactive power capability of WPP is decreasing fast. This can be of concern when the power system is under stressed conditions. Power system studies done with lower resolution time-series data (e.g. 30-min) will be affected if fluctuations in wind speed are neglected. Therefore, although wind power fluctuations can be neglected for power system studies requiring reactive power data at 1-min time resolution, however, neglecting power fluctuation in 30-min time resolution power system studies will have large error with respect to reactive power capability.

It is to be noted that both positive and negative ramping of reactive power capability from WPP is limited by the GSC ramp limiter. From the duration curves in Fig. 5, the most interesting point is around 100% of the curves when there is decrease in reactive power capability as denoted by negative ramp rates. For long-term voltage stability studies, this can be crucial if the power system is stressed and requires maximum reactive power support from WPP. Therefore,
It can be observed from Fig. [6] that reactive power capability ramping is increasing beyond 0.85 p.u. Below that reactive power capability ramping is decreasing. This is because minimum reactive power capability is around maximum active power production from WPP which is at and above rated wind speeds. Since at such wind speeds, WPP production is at the flat part of power curve, active power fluctuation is less. The same is reflected in reactive power capability which is ramping less around minimum reactive power capability for all 3 duration curves. Seen from the PQ capability curve shown in Fig. [3] WPP has additional reactive power even at rated active power output. Since at rated active power, effect of fluctuation of wind speed is less, fluctuation in reactive power capability is also less. In this study, wind gusts which causes active power output from individual WT generator to exceed rated active power output, are not considered because the effect of wind gusts is valid for individual WTs, but at the WPP level effect of wind gusts are smoothened out.

4 SUMMARY AND POSSIBLE FUTURE WORK

This paper investigates effects of active power fluctuation on reactive power capability of a WPP. For this purpose Horns Rev 2 WPP is chosen as a case study. One year time series data for active power with fluctuations is simulated to calculate reactive power injection capability of the considered WPP. Reactive power capability ramp rate for different time periods - 1-min, 10-min and 30-min - are calculated and duration curve for each of these time periods are analysed to observe that that active power fluctuation has substantial impact in reactive power capability of WPPs; especially if the time resolution of the sampled data is low. These observations are particularly important for long-term power system studies, in order to minimise the error introduced by neglecting wind power fluctuations.
The preliminary work presented here shows opportunities for further research:

- This paper only looked into reactive power injection capability. Similar studies also need to be done for reactive power absorption capability.
- Quantify fluctuation in reactive power capability for per unit fluctuation in active power.
- In this paper duration curve was plotted for the entire time-series without taking into consideration initial active power production. However, the active power fluctuations vary largely with the initial condition because of the highly non-linear power curve. Further studies can be done to see how initial condition affects ramping of reactive power capability.
- Reactive power capability can be either be converter voltage limited or converter current limited. There is a switching from voltage limitation to current limitation depending on grid voltage and active power production. It can be interesting to analyse whether there is any switching between voltage and current limitation due to wind power fluctuation.

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