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Minimizing wind power curtailments using OPF considering voltage stability

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Abstract

As the amount of wind power in power systems has increased it has become necessary to curtail wind power in some high-penetration situations. In order to assess the need for curtailment arising from voltage stability considerations we develop a security constrained optimal power flow for minimizing the expected curtailment. We find that with a very high wind penetration and wind farms operating at unity power factor curtailment becomes necessary to satisfy voltage limits. In this case the optimal solution in the studied system is to curtail at a single bus rather than curtailing by a smaller amount at several buses. However, allowing for reactive power production from wind farms reduces the need for curtailments.

1 Introduction

The last decade has seen a rapid increase in installed wind power capacity world-wide, with some European countries generating more than 20% of annual electricity production from wind power [1]. This increase has been accompanied by increased wind power curtailments [2].

By the end of 2017 Sweden had about 6700 MW of installed wind power capacity and a yearly production around 17 TWh, equivalent to about 11% of total generation. The installed wind power capacity is expected to increase significantly the coming years, which means that wind power curtailment could become necessary. In the Swedish transmission system, which is characterized by large transfer of hydro power from the north to the south, some transmission limits are set by voltage stability considerations [3].

In this paper, we develop an optimal power flow to minimize the expected curtailments of wind power, subject to security constraints under contingencies and different wind power scenarios. The objective is to investigate if curtailments due to voltage stability-induced transmission limits may be necessary. Hence the need for a full AC power flow, as opposed to a DC power flow with transmission constraints on lines.

Many previous works concern optimal planning of wind power capacity. For example, [4] uses a long-term voltage stability constrained OPF to find the optimal capacity allocation of wind power in order to maximize the voltage stability margin. However, here the focus is on the short term problem given the market outcome. For the short-term decision problem, the security constrained optimal power flow (SCOPF) is widely used [5]. A SCOPF considers both preventive actions affecting the current operating state and corrective actions affecting the operating state after possible contingencies. Although there is a literature on SCOPF in the context of uncertainty caused by renewable generation [6] [7] there are not so many studies that focus explicitly on wind power curtailments. In [8] an OPF with FACTS devices is proposed to illustrate how FACTS can provide reactive power support and thus help reduce curtailments.

2 Problem formulation

Let the total set of scenarios be denoted $\mathcal{S}$. A scenario is a realization of the system that may include a contingency event, such as tripping of a line or generator, or realization of an uncertain parameter, such as a change in wind power production or load. Further, let $\mathcal{W}$ denote the set of wind farms, $\mathcal{G}$ the set of conventional generators, $\mathcal{W}_i$ the set of wind farms at bus $i$, $\mathcal{G}_i$ the set of conventional generators at bus $i$, $\mathcal{G}_i$ the set of conventional generators providing reserves, and $\hat{\mathcal{G}}_i$ the set of conventional generators at bus $i$ providing reserves. A generator providing reserves has variable active power in the different scenarios.

The objective function to be minimized is given by

$$
\mathbb{E} \left( \sum_{j \in \mathcal{W}} P_{w,j}^s \beta_j^s \right) = \sum_{s \in \mathcal{S}} p^s \sum_{j \in \mathcal{W}} P_{w,j}^s \beta_j^s
$$

where $p^s$ is the probability of scenario $s$, $P_{w,j}^s$ is the realization of production for wind farm $j$ under scenario $s$, and $\beta_j^s$ is
the fraction of curtailed wind power for farm \( j \) under scenario \( s \). The mismatch equations for the market outcome or base scenario, prior to uncertainty realization, are given by

\[
P_i(\mathbf{V}, \mathbf{\theta}) = \sum_{j \in \mathcal{W}} P_{w,j} + \sum_{j \in \mathcal{G}} P_{g,j} - P_{d,i} \tag{2}
\]

\[
Q_i(\mathbf{V}, \mathbf{\theta}) = \sum_{j \in \mathcal{W}} Q_{w,j} + \sum_{j \in \mathcal{G}} Q_{g,j} - Q_{d,i} \tag{3}
\]

where the left hand side represents the power flow equations for the base state, with voltage magnitudes given by \( \mathbf{V} \) and bus angles given by \( \mathbf{\theta} \), and the right hand side is the net power injection into each node, given by generation minus load. The mismatch equations for the considered scenarios are given by

\[
P_i(\mathbf{V}^s, \mathbf{\theta}^s) = \sum_{j \in \mathcal{W}} P_{w,j}^{s} (1 - \beta_j^s) + \sum_{j \in \mathcal{G}} P_{g,j}^s, \quad j \in \tilde{\mathcal{G}} \tag{4}
\]

\[
Q_i(\mathbf{V}^s, \mathbf{\theta}^s) = \sum_{j \in \mathcal{W}} Q_{w,j}^{s} + \sum_{j \in \tilde{\mathcal{G}}} Q_{g,j}^{s} - (1 + \lambda_j^s)Q_{d,i} \tag{5}
\]

where we note that a load increase \( \lambda_j^s \) has been applied, the curtailment factor \( \beta_j^s \) has been applied to the realized wind generation, and that the active power of generators providing reserves have been adjusted to \( P_{g,j}^s \). The bus voltage magnitudes and angles for scenario \( s \) are given by \( \mathbf{V}^s \) and \( \mathbf{\theta}^s \).

In order to limit the reactive power production of wind farms and conventional generators the following constraints are applied

\[
|Q_{w,j}^s| \leq \kappa_w P_{w,j}^s (1 - \beta_j^s), \quad j \in \mathcal{W} \tag{6}
\]

\[
|Q_{g,j}^s| \leq \kappa_g P_{g,j}^s, \quad j \in \tilde{\mathcal{G}} \tag{7}
\]

\[
|Q_{g,j}^s| \leq \kappa_g P_{g,j}^s, \quad j \in \mathcal{G} \setminus \tilde{\mathcal{G}} \tag{8}
\]

where \( \kappa_w \) and \( \kappa_g \) are appropriate constants regulating the power factor of wind farms and conventional generators.

Letting all optimization variables be denoted by

\[
\mathbf{x} = [\mathbf{\theta} \; \mathbf{V} \; (Q_{g,j})_{j \in \mathcal{G}} \; (Q_{w,j})_{j \in \mathcal{W}} \; \ldots \; (\kappa_{w}^s P_{w,j}^s (1 - \beta_j^s), \; j \in \mathcal{W} \; \ldots]\tag{9}
\]

the optimization problem can be written compactly as

\[
\min_{\mathbf{x}} f(\mathbf{x}) \text{ s.t. } \begin{align*}
g(\mathbf{x}) &= 0 \\
h(\mathbf{x}) &\leq 0
\end{align*} \tag{10}
\]

where \( f \) is given by (1), \( g \) is given by (2)-(5), and \( h \) includes (6)-(8) as well as possible line flow constraints and fixed limits for all variables. Note that the reason that active powers in the base scenario are not included as optimization variables is that they are regarded as set by the market outcome. Active powers in the base scenario are instead taken as parameters resulting from a regular power flow.

### 3 Case studies

The problem was implemented in Matlab using Matpower [9] and solved on the Nordic 32 model of the Swedish power system [10], shown in Figure 1. The system is divided into four areas, North, Central, Southwest, and External. Most of the load is located in Central, as shown in Table 1. In the original system, North exports about 3200 MW to Central. The original system has 23 generators.

For our case studies, the following modifications have been made to the original system. First, the transfer from North to Central has been increased by 400 MW, by proportionally increasing the generation in North and decreasing the generation in Cen-
Table 1: Summary of load flow for original Nordic 32 system

| Area    | Generation (MW) | Load (MW) | Losses (MW) |
|---------|-----------------|-----------|-------------|
| North   | 4630            | 1180      | 266         |
| Central | 2850            | 6070      | 150         |
| Southwest | 1590      | 1390      | 14          |
| External | 2300            | 2300      | 0           |
| Total   | 11370           | 10940     | 430         |

Table 2: Considered cases

| Case  | Description                                                                 |
|-------|-----------------------------------------------------------------------------|
| C1    | Wind power PF 1 ($\kappa_w = 0$) at all 130 kV and 220 kV buses in North: 1011, 1013, 1014, 1012, 1022, 1021, 2031, 2032, generator 24-31         |
| C2    | Same as C1, but no wind power at bus 1021                                    |
| C3    | Same as C1, but wind power between PF 0.9 lead/lag ($\kappa_w = 0.48$)     |

tral. Wind generators have also been added in North. In the base scenario load flow, the generation at regular generators in North (excluding the slack bus 4011) has been scaled down to accommodate the injected wind power.

As an indication of the amount of wind power, the penetration is calculated as the fraction of conventional generation in North excluding the slack bus displaced by wind power, in the power flow for the base scenario. We consider three different cases, described in Table 2. For each case the optimization problem is solved for increasing penetration levels, starting at 0.8 and going up to 0.995.

In these case studies we do not consider any contingencies. Instead, we include a single scenario, which is an increase in wind generation by 20%. As there is only a single scenario, the expected curtailment is the realized curtailment for this scenario. Conventional generators have $\kappa_q = 1$. Since we are interested only in voltage stability we do not include thermal transmission limits on lines. Voltage limits are 0.9 and 1.1 pu for all buses. The generators on buses 4047, 4051, and 4063, which represent nuclear generation, and on buses 4071 and 4072 in External have been fixed, and the remaining generators have variable active power, i.e. belong to $\tilde{G}$.

Figure 2 shows the curtailment for all cases. In case C1 the curtailment increases from 0 starting at 0.85 penetration to reach about 250 MW for the highest penetration. The curtailment is lower for C2 when there is no wind at bus 1021. Note that this means a concentration of the wind generation in fewer buses. Bus 1021 was chosen because this was the bus where wind was curtailed for C1. In C3 wind farms can operate at any power factor between 0.9 leading and 0.9 lagging and there is no curtailment.

To better explain the results, figure 3, 4, and 5 show the active and reactive power generation and the voltage magnitude for case C1 for the maximum penetration level 0.995. As seen in Figure 3, all conventional generators in North except the slack bus 4011 have been reduced to close to zero, and replaced by the wind at generators 24-31. In the wind increase scenario, the generation in North has been redistributed to other generators, and a single wind generator at bus 1021 curtailed. Comparing with the reactive power in Figure 4, it is seen that generators 5,8,11, and 12 have their reactive power constrained by the active power, i.e. (7) is binding. Active power production has been allocated to these generators since these are the most critical buses for providing reactive power support. The reason why there has to be curtailment is so that generators in North can increase their active and thus reactive power production, in order to maintain the voltages in the system at acceptable levels.

In Figure 5 it is seen that bus 1021 where the curtailment occurs is well inside the voltage range of 0.9-1.1 pu. However, several other buses are at their maximum voltage limit. The reason is that there is a lack of reactive power in the system, so generators that have capacity for producing more reactive power will do so to help maintain the voltages and the transmission capacity from North to Central, until they reach the maximum local voltage limit at their respective bus.

Figure 6 shows the active power production for case C2. Now the curtailment occurs at bus 1014 instead, and the overall curtailment level is lower. The reason is that wind generation is now concentrated at fewer buses that are positioned better from an electrical point of view. As can be expected, curtailment occurs first at remote buses with limited reactive power capabilities, such as bus 1021 and 1014.

Allowing wind generators to produce at variable power factor eliminates the need for curtailment. Figure 7 shows the reactive power generation for case C3. Most wind generators are injecting
Figure 3: Active power of generators for 99.5% penetration in North for case C1.

Figure 4: Reactive power of generators for 99.5% penetration in North for case C1.

Figure 5: Voltage magnitudes of buses for 99.5% penetration in North for case C1.
Figure 6: Active power of generators for 99.5% penetration in North for case C2 with no wind power at bus 1021.

Figure 7: Reactive power of generators for 99.5% penetration in North for case C3 with wind farms within power factor 0.9 lead/lag.

Figure 8: Voltage magnitudes of buses for 99.5% penetration in North for case C3 with wind farms within power factor 0.9 lead/lag.
reactive power into the grid. As shown in Figure 8 all voltages are now within limits.

It is important to note that there is not a set limit for the amount of wind power that can be transferred from North to Central. For example, as Figure 2 shows, for case C1 the base scenario wind power increases by about 100 MW from 0.94 to 0.96 penetration. However the curtailment in the wind increase scenario increases only by 50 MW. The reason is that after curtailing one of the wind farms, the remaining wind power has a better distribution from a grid point of view so that more power can be transferred with lower losses and reactive power consumption. Figure 9 shows the total wind generation after curtailment minus the losses in the system for the 20% wind increase. This shows how effectively wind generation is replacing conventional generation. Since more wind means higher transfer from North to Central and hence higher losses the marginal contribution of extra wind generation decreases. However, the net contribution of extra wind power is always positive, so that conventional generation can be further reduced for increasing wind penetration even as curtailment becomes necessary.

4 Conclusions

Using a security constrained optimal power flow we have shown that a decrease in the capacity for voltage regulation as conventional generation is replaced by wind may produce the need for curtailment of wind power to maintain acceptable voltages in the system. In the studied system curtailing at a specific bus gives a more favourable distribution of the generated power and hence allows an increased transfer from the exporting area.

However, curtailment is only necessary for high wind penetrations and if wind generators are unable to provide reactive power support. In a real system, such as the Nordic power system, there may be other factors that limit the instantaneous penetration of wind power before voltage stability considerations, such as a minimum acceptable inertia level or the need to keep conventional generation online to provide frequency control.

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