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C4-1016

AORC Technical meeting 2014

Voltage Stability Margin Affected by High Wind Power Penetration

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SUMMARY

Although increasing wind power penetration into power grids is beneficial and helps to replace conventional power generation with these clean power resources, it can bring several stability challenges into the power systems. Most of these issues stems from intermittent nature of this renewable sources. In this paper, voltage stability affected by wind power penetration to the grids is investigated. This is done through a purposed convex optimization problem where the objective is to maximize the loadability of system which is directly associated with the voltage collapse point. There are some cases that high penetration of wind power into the grid can jeopardize the voltage stability margin (VSM) of the grid. We show that if a system operator (SO) is to ensure a certain VSM during the real time operation of power system, a huge amount of wind power should be curtailed. This is not economical and desirable. The aim is to evaluate how much wind power is to be curtailed at different wind power penetration levels in order to guarantee a certain VSM at all scenarios and how this curtailed amount can be reduced.

KEYWORDS

Wind Power Penetration – Voltage Stability – Maximum Loadability

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1. Introduction

Nowadays, due to lack of a strong interconnection between electric power systems within EU, there is a concern about the restricted power exchange.

One of the reasons of improving the level of power exchange is development of renewable energy sources such as offshore wind farms. The total capacity of wind energy installed in Europe by the end of 2009 was about 76 GW [1]. This amount is predicted to be about 180 GW including 35 GW offshore, and 300 GW including 120 GW offshore for 2020 and 2030, respectively [2]. Therefore, such offshore wind farms connections have become the main attention point of some countries such as Germany, Denmark, Sweden, United Kingdom and Netherlands for future implementation. This uncertainty can cause additional operating costs for energy procurement from hour/day-ahead markets. Several techniques have been employed to incorporate such uncertainty of wind power generation [3]–[6]. This highly variable nature of wind power can significantly affect the stability of power systems, particularly the voltage stability.

We propose a procedure in which the system operator (SO) assesses the voltage stability status associated with each forecasted wind power scenario. In this paper, the voltage stability assessment is done by obtaining the maximum loadability of the system which is directly connected to voltage collapse point in the PV curve for all probable scenarios. This is achieved by solving a convexified AC optimization problem in the form of second order cone programming proposed in [9].

It is shown that if SO is interested in assuring that the system operating point in the presence of high wind power injection locates in a secure distance from the point of collapse (maximum loading of the system), some part of wind generation needs to be curtailed. Subsequently, we show that by modifying some parameters of existing devices in the network the secure distance from point of collapse can be reached while a lower wind power curtailment is needed.

2. Mathematical Model

The proposed OPF is a convex optimization problem in the form of Second Order Cone Programming (SOCP) as follows:

$$\begin{aligned} &\textit{Maximize} \;\; \lambda \;\; (\mathbf{LO}) \\ &\textit{Subject to} \\ &\qquad \mathbf{AXo} = \mathbf{b} \;\; (\mathbf{LE}) \\ &\qquad \underline{\mathbf{Xo}} \leq \mathbf{Xo} \leq \overline{\mathbf{Xo}} \;\; (\mathbf{LI}) \\ &\qquad \mathbf{Xo} \in \mathbf{C} \;\; (\mathbf{CI}) \end{aligned} \quad (1)$$

SOCP is a convex problem which can be introduced as a general form of linear programming accompanied by nonlinear constraints which are in form of convex cones. Many kinds of problems such as LP and QP can be formulated as SOCPs and be efficiently solved through polynomial time IPMs [7], [8].In above OPF problem, ***Xo*** is the optimization variable vector **A** and **b** are constant vectors. **C** is a convex set which has the form of convex cones. In this paper the nonlinear constraints are recast as rotated quadratic cones. SOCP has a linear objective function (**LO**) subjected to a set of linear equality (**LE**), linear inequality (**LI**) and convex conic inequality (**CI**) constraints. The detail of constraints can be found in [9]. λ is the loading factor which is defined as follows:

$$\begin{aligned} P_{Di} &= \lambda P_{Di0} \\ Q_{Di} &= \lambda Q_{Di0} \end{aligned} \quad (2)$$

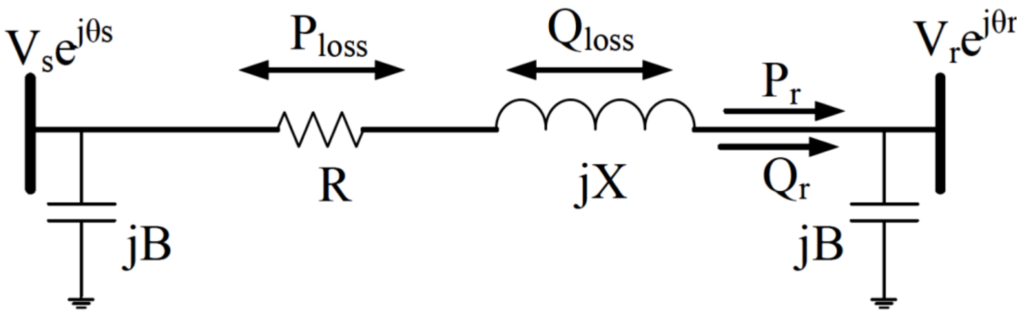

Figure 1. The equivalent circuit of an AC line

Where $\boldsymbol{P_{Di0}}$ and $\boldsymbol{Q_{Di0}}$ are the base loads in the network. To derive the model AC line variables shown in Figure 1 are used. Using these variables a set of equations is derived. This set of equations was first developed in [9] for solving an economic dispatch problem of hybrid AC-DC grids. The optimization problem used in this paper to assess the voltage stability margin is as follows:

$$
\begin{gathered}
\textit{Maximize} \ \ \lambda \\
\textit{Subject to} \\
\boldsymbol{P_G} - \boldsymbol{\lambda P_D} - \boldsymbol{M_F P_r} - \boldsymbol{M_l P_{loss}} - (Pw - WPC) = 0 \\
\boldsymbol{Q_G} - \boldsymbol{\lambda Q_D} - \boldsymbol{M_F Q_r} - \boldsymbol{M_l Q_{loss}} - \boldsymbol{BW} = 0 \\
2\boldsymbol{RP_r} + 2\boldsymbol{XQ_r} + 2\boldsymbol{RP_{loss}} + 2\boldsymbol{XQ_{loss}} - \boldsymbol{M_W W} = 0 \\
\mathbf{CXP_r} - \mathbf{CRQ_r} = 0 \\
\boldsymbol{P_{loss}} \ = \boldsymbol{2R\tilde{P}_{loss}} \\
\boldsymbol{XP_{loss}} - \boldsymbol{RQ_{loss}} = 0 \\
\boldsymbol{2\tilde{P}_{loss} W_r} \ \geq \boldsymbol{P_r^2} + \boldsymbol{Q_r^2}
\end{gathered} \quad (3)
$$

where $\mathbf{C_{nc*nl}}$ (c, *l*) is 1 if line *l* is in the loop *c* with the same direction, -1 with the opposite direction, and otherwise it is zero. According to graph theory, nc is the number of independent loops in a graph ($n_c = n_l - n_b + 1$). $\mathbf{M}_{Wnl*nb}$ is the transpose of matrix $\mathbf{M_F}$. W and Wr are vectors indicating square of voltage magnitudes of buses and receiving end buses, respectively. ***Pw*** is the wind power generation and ***WPC*** is wind power curtailment. In above optimization problem, $\mathbf{P_G}$ is a vector of active power generation at each AC bus with size of n_{b*1} which has only n_G non-zero elements. $\mathbf{Q_G}$ is a vector of reactive power generation at each AC bus with size of n_{b*1} which has only n_G non-zero elements. $\mathbf{P_D}$ and $\mathbf{Q_D}$ are two vectors containing active and reactive power loads at each AC bus. **Pr** and **Qr** are two vectors containing active and reactive line flow powers at receiving end of AC lines. $\mathbf{P}_{loss}$ and $\mathbf{Q}_{loss}$ are two vectors containing AC line flow active and reactive power losses on AC lines.

3- SIMULATION RESULTS

To investigate the impact of high wind penetration on the voltage stability margin, IEEE 30 bus test system is used [10]. The proposed problem is coded in GAMS and solved using its embedded solver MOSEK [11].

It is assumed that a wind farm is connected to bus number 26. We assume the forecasted scenarios for wind farm are given in Table I.

TABLE I
WIND POWER SCENARIOS

Scenario	1	2	3	4	5	6	7	8	9
Forecasted wind power (MW)	5.83	24.16	42.5	60.83	79.16	97.5	110	120	130

Firstly, the lodability factor for all these scenarios without considering any wind power curtailment is calculated and reported in Table II.

TABLE II
MAXIMUM LOADABILITY WITHOUT WIND POWER CURTAILMENT AND BASE LIMITS

Scenario	1	2	3	4	5	6	7	8	9
λ	1.68919	1.70680	1.69244	1.64812	1.57016	1.44519	1.30977	1.10774	0.65051

For the first case, we use optimization model in (3) where ***WPC*** is set to zero. As it is seen the loading factor which is associated with the distance from voltage collapse point is even lower than base value for those high levels of wind power scenarios.

Secondly, if the SO is to take into account a specific margin for voltage stability for all wind power scenarios through the wind power curtailment, he can use model in (3) where ***WPC*** is free to get any value less than ***Pw***. In this case, the calculated loading factors are obtained and given in Table III.

TABLE III
MAXIMUM LOADABILITY WITH WIND POWER CURTAILMENT AND BASE LIMITS

Scenario	1	2	3	4	5	6	7	8	9
λ	1.68919	1.70680	1.70681	1.70680	1.70680	1.70679	1.70678	1.70674	1.70663
WPC (MW)	0	0.00137	17.56612	35.89925	54.23259	72.56552	85.06488	95.06389	105.06370

In this case, the total curtailed wind power is 465.457MW. Therefore, if the SO is to consider a certain VSM, some curtailment is needed. There are different ways to reduce this curtailed wind power.
However, this is not the scope of this paper. Here we propose modifying the reactive power limits of synchronous condensers at buses 5, 8, 11 and 13 as 120, 150, 50 and 70Mvar, respectively. This allows us to have a loading factor larger than 2.5 and at the same time a lower curtailed wind power as shown in Table IV. In this case we have the total 387.4MW curtailment which is lower than the curtailment with the base power limits of synchronous condensers.

TABLE IV
MAXIMUM LOADABILITY WITH WIND POWER CURTAILMENT AND MODIFIED LIMITS

Scenario	1	2	3	4	5	6	7	8	9
λ	2.88759	2.94142	2.95007	2.95007	2.95007	2.95006	2.95005	2.95002	2.94993
WPC (MW)	0	0	24.74680	24.74680	43.08032	61.41375	73.91415	83.91545	93.92029

4- CONCLUSION

In this paper we propose a procedure where the system operator (SO) can assess the voltage stability status associated with each forecasted wind power scenario injected to the power system. In this paper, the voltage stability assessment is done by obtaining the maximum loadability of the system which is directly connected to voltage collapse point in the PV curve for all probable scenarios. It is shown that if SO is interested in assuring that the system operating point in the presence of high wind power injection locates in a secure distance from the point of collapse (maximum loading of the system), some part of wind generation needs to be curtailed. Subsequently, we show that by modifying some parameters of existing devices in the network the secure distance from point of collapse can be reached while a lower wind power curtailment is needed.

5- BIBLIOGRAPHY

[1] "A breath of fresh air, ewea 2009 annual report." European Wind Energy Association., April 2010. [Online]. Available: http://www.ewea.org/fileadmin/ewea documents/documents/ publications/reports/Ewea Annual Report 2009.pdf

[2] "Pure power - wind energy scenarios up to 2030," European Wind Energy Association., March 2008. [Online]. Available: http://www.ewea.org/fileadmin/ewea documents/documents/ publications/reports/purepower.pdf

[3] L. Shi, C. Wang, L. Yao, Y. Ni, and M. Bazargan, "Optimal power flow solution incorporating wind power," Systems Journal, IEEE, vol. 6, no. 2, pp. 233–241, 2012.

[4] P. Yu and B. Venkatesh, "A practical real-time opf method using new triangular approximate model of wind electric generators," Power Systems, IEEE Transactions on, vol. 27, no. 4, pp. 2036–2046, 2012.

[5] Y. Atwa and E. El-Saadany, "Probabilistic approach for optimal allocation of wind-based distributed generation in distribution systems," Renewable Power Generation, IET, vol. 5, no. 1, pp. 79–88, 2011.

[6] T. Amraee, A. Soroudi, and A. Ranjbar, "Probabilistic determination of pilot points for zonal voltage control," Generation, Transmission Distribution, IET, vol. 6, no. 1, pp. 1–10, 2012.

[7] M. S. Lobo, L. Vandenberghe, S. Boyd, and H. Lebret, "Applications of second-order cone programming," Linear Algebra and its Applications, vol. 284, no. 1-3, pp. 193 – 228, 1998.

[8] F. Alizadeh and D. Goldfarb, "Second-order cone programming," Mathematical Programming (Series B), vol. 95, no. 1, pp. 3–51, 2003. [Online]. Available: http://rutcor.rutgers.edu/ alizadeh/CLASSES/03sprNLP/Papers/allSurvey.pdf

[9] M. Baradar, M. Hesamzadeh, and M. Ghandhari, "Second-order cone programming for optimal power flow in vsc-type ac-dc grids," Power Systems, IEEE Transactions on, vol. 28, no. 4, pp. 4282–4291, 2013.

[9] "The University of Washington Power Systems Test Case Archive", [On-line]. Available: http://www.ee.washington.edu/research/pstca/

[11] "Gams/mosek." [Online]. Available: http:www.gams.com/dd/docs/solvers/mosek.pdf