Electric Power Systems Research 116 (2014) 408–418

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

# A risk-averse security-constrained optimal power flow for a power grid subject to hurricanes

Pirooz Javanbakht*, Salman Mohagheghi

*Department of Electrical Engineering and Computer Science, Colorado School of Mines, 1610 Illinois Street, Golden, CO 80401, USA*

ARTICLE INFO

*Article history:*
Received 3 May 2014
Received in revised form 17 June 2014
Accepted 10 July 2014
Available online 1 August 2014

*Keywords:*
Contingency analysis
Generation dispatch
Hurricanes
Natural disasters
Optimal power flow
Risk analysis

ABSTRACT

During the course of a hurricane, many components in the power grid may be affected. In particular, loss of transmission lines and/or towers due to excess wind conditions may adversely impact the operation of the grid and force a re-dispatch of the generation units. However, large generation units have considerable ramp rates and usually are not able to vary their outputs fast enough. This might lead to temporary imbalances between load and generation that, if not resolved quickly, may result in more severe cascading failures. When a large scale disturbance such as a hurricane is forthcoming it is most beneficial to proactively dispatch the grid so as to minimize the likelihood of future failures. To assist the operator in proactively responding to an imminent event such as a hurricane, a risk-averse generation dispatch model is presented in this paper based on security-constrained AC optimal power flow. To perform ($N$–$k$) contingency analysis, a geospatial model of the power grid is developed that allows for the computation of outage probabilities of the transmission lines affected by the hurricane wind fields. Statistical analysis has been performed on the historical data on the past hurricane events in the US in order to simulate realistic hurricane scenarios. The IEEE 118-bus test system has been mapped onto the map of the state of Texas in order to provide a realistic test bed. The proposed algorithm takes into account the cost of operation, as well as the risks associated with overload and over/undervoltage conditions. Moreover, it allows for preventive as well as corrective dispatch of the power grid.

## 1. Introduction

Natural disasters have been considered as one of the two main causes of the largest blackouts in North America (the other being cascading failures) [1]. As one of the most severe types of natural disaster events, a hurricane can cause major damage and devastation to the critical infrastructure of the affected cities. When it comes to hurricanes, power grids are not necessarily immune and have been shown to be severely affected in the past [1–3]. High winds can potentially damage the overhead lines and towers/poles, while high floodwater as a result of heavy rains and hurricane surge may lead to flooding of substations. The colossal amount of destructive energy released during the course of a high-intensity hurricane makes it impractical, if not infeasible, to guarantee the continuous secure operation of all grid components. At the same time, the uncertain and infrequent nature of the event prevents utilities from reinforcing the grid through conservative and costly designs.

One way to address this issue is to adjust the generation dispatch before the onset of an imminent natural disaster event. Here, the system operator can put in place a control strategy that proactively dispatches the system in anticipation that some sections/resources may become affected by the event and hence may become unavailable. Power grid operation subject to disturbances has been extensively addressed in the literature within the context of security-constrained optimal power flow (SCOPF) [4,5]. Here, the objective is to ensure that the system remains robust with respect to credible contingencies, and the system constraints are maintained should one of these contingencies happen. Traditionally, this was done through performing deterministic security assessment, where all contingencies are assumed to have equal probabilities of occurrence. This could create problems since it would emphasize on very severe events, making the solution overly conservative [6]. In order to incorporate the uncertain nature of disturbances, some have adopted stochastic approaches for solving the OPF and SCOPF problems. For instance, Yong and Lasseter [7] incorporated the expected value of reserve uncertainties into the objective function of the OPF. Minimizing the expected generation cost of various contingencies, in addition to the pre-contingency cost, has been reported in Ref. [8]. Multi-stage stochastic optimization

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* Corresponding author. Tel.: +1 303 869 5040.
*E-mail address:* pjavanba@mymail.mines.edu (P. Javanbakht).

http://dx.doi.org/10.1016/j.epsr.2014.07.018
0378-7796/

## Nomenclature

### *A. Indices*

| | |
|---|---|
| $c$ | contingency index ($c = 0$ for normal operating condition) |
| $h$ | hurricane index |
| $i$ | generator index |
| $j$ | line index |
| $k$ | bus index |
| $l$ | hurricane eye location index ($l = 0$ indicates landfall) |
| $p$ | hurricane track (path) index |
| $s$ | hurricane scenario index |

### *B. General parameters*

| | |
|---|---|
| $a_i$, $b_i$, $c_i$ | coefficients of the cost function for generator $i$ |
| $c^g$ | mode control parameter that determines preventive or corrective dispatch modes. $c^g = 0$ for preventive dispatch, $0 < c^g \leq 1$ for corrective dispatch |
| NB | number of buses |
| NC | number of contingencies |
| NG | number of generators |
| NL | number of lines |
| $\mathrm{NL}_c$ | number of lines in a contingency $c$ |
| NP | number of hurricane tracks (paths) |
| NT | number of 2-h simulation time steps |
| $P_i^{G,\max}$ | maximum permissible active power injection by generator $i$ |
| $P_i^{G,\min}$ | minimum permissible active power injection by generator $i$ |
| $Q_i^{G,\max}$ | maximum permissible reactive power injection by generator $i$ |
| $Q_i^{G,\min}$ | minimum permissible reactive power injection by generator $i$ |
| $S_j^{\max}$ | capacity (rating) of transmission line $j$ |
| $V_k^{\max}$, $\theta_k^{\max}$ | maximum permissible voltage magnitude and phase angle at bus $k$ |
| $V_k^{\min}$, $\theta_k^{\min}$ | minimum permissible voltage magnitude and phase angle at bus $k$ |
| $\alpha$ | hurricane land decay factor |
| $\alpha^r$, $\alpha^l$, $\alpha^v$ | cost function weighting coefficients |
| $\beta$ | modeling factor specifying the hurricane boundary |
| $\rho_{j,c}$ | soft upper limit on the percentage of transmission line $j$ capacity (rating) that can be used under contingency $c$. If all the capacity can be used: $\rho_{j,c} = 1$. This indicates a soft constraint on the flow of the transmission line which can be violated subject to a penalty. |
| $\rho_{j,c}^{\max}$ | hard upper limit on the percentage of transmission line $j$ capacity (rating) that can be used under contingency $c$ (note: $\rho_{j,c}^{\max} \geq \rho_{j,c}$). This indicates a hard constraint on the flow of the transmission line which cannot be violated at any time. |
| $\theta_{k1,k2}^{\min/\max}$ | minimum or maximum permissible phase angle between buses $k1$ and $k2$ |

### *C. Power system variables*

| | |
|---|---|
| $P_{i,c}^G$, $Q_{i,c}^G$ | active and reactive power of generator $i$ during contingency $c$ ($c = 0$ indicates normal operation) |
| $\mathrm{Pr}_c$ | probability of contingency $c$ |
| $S_j$ | apparent power flow through transmission line $j$ |
| $V_{k,c}$, $\theta_{k,c}$ | voltage magnitude and phase angle at bus $k$ under contingency $c$ |
| $Y_c$ | admittance matrix of the network for contingency $c$ |
| $Y_{kk',c}$ | $(k, k')$-th entry of $Y_c$ |
| $\delta_{j,c}^l$ | overload severity variable for line $j$ during contingency $c$ |
| $\delta_{j,k}^v$ | over/undervoltage severity variable for bus $k$ during contingency $c$ |
| $\theta_{k1,k2,c}$ | phase angle between buses $k1$ and $k2$ during contingency $c$ |

### *D. Hurricane variables*

| | |
|---|---|
| $d_{\max}(j, h)$ | maximum distance between transmission line $j$ and the eye of hurricane $h$ |
| $d_{\min}(j, h)$ | minimum distance between transmission line $j$ and the eye of hurricane $h$ |
| $\mathrm{out}_j$ | event indicating the outage of transmission line $j$ as a result of hurricanes |
| $\Delta P_{0,s}$ | difference between the pressure at the hurricane eye location and the pressure at $r_s$ for scenario $s$ (in mb), for a hurricane at landfall |
| $\Delta P_{l,s}$ | difference between the pressure at the hurricane eye location and pressure at $r_s$ for scenario $s$ (in mb), for a hurricane at eye location $l$ |
| $\mathrm{Pr}_s$ | normalized probability of scenario $s$ |
| $r_s$ | hurricane size: the radius of the area affected by the hurricane (in nautical miles, nm) |
| $r_{mw}$ | radius to maximum wind speed (in nautical miles, nm) |
| $t$ | time elapsed after hurricane landfall (in h); $t = 0$ indicates landfall |
| $\hat{w}_j$ | expected value of the maximum wind speed to which transmission line $j$ is exposed |
| $\hat{w}_{j,p}$ | expected value of the maximum wind speed to which transmission line $j$ is exposed if hurricane travels along track $p$ |
| $w_m$ | maximum sustained wind speed (in nautical miles per hour, kt) |
| $W(x)$ | static wind field; as a function of distance to the hurricane eye |
| $x$ | distance to the hurricane eye |
| $x_0$ | hurricane eye location at landfall |
| $v$ | hurricane translational speed |
| $\varphi_t$ | latitude (in degrees) at time $t$ |
| $\varphi_l$ | latitude (in degrees) at eye location $l$ |
| $\psi_t$ | longitude (in degrees) at time $t$ |
| $\psi_l$ | longitude (in degrees) at eye location $l$ |

formulations have also been proposed [9,10], where event uncertainties are handled through the usage of second (or multi) stage recourse variables. At the same time, acknowledging the fact that inequality constraints in the OPF/SCOPF problem are not always rigid, and may be allowed to be slightly violated at times, some have used techniques based on chance constrained optimization [11,12], where inequality constraints are met with a certain probability. In a different approach, cumulant method was used to solve the uncertainties of the OPF problem [13].

However, in most of these approaches based on SCOPF, the exposure of the system to failure as a result of a contingency is either unknown or modeled subjectively. In fact, SCOPF does not differentiate between the contingencies with severe impacts on the system and those with minor impacts. Rather, it only ensures that there exists a low cost feasible solution satisfying all the contingencies as well as the normal operating condition, without considering the quality of that solution in terms of system security. To solve this issue, risk-based security assessment was proposed [6], where the notion of risk was modeled as a combination of severity of a