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Assessment of post-contingency congestion risk of wind power with asset dynamic ratings

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ABSTRACT

Large scale integration of wind power can be deterred by congestion following an outage that results in constrained network capacity. Post outage congestion can be mitigated by the application of event control strategies; however they may not always benefit large wind farms. This paper investigates this problem in detail and proposes an advanced mathematical framework to model network congestion as functions of stochastic limits of network assets to capture post contingency risk of network congestion resulting through the constrained network capacity that limits high penetration of wind. The benefit of this approach is that it can limit the generation to be curtailed or re-dispatched by dynamically enhancing the network latent capacity in the event of outages or as per the need. The uniqueness of the proposed mathematical model is that it converts conventional thermal constraints to dynamic constraints by using a discretized stochastic penalty function with quadratic approximation of constraint relaxation penalty. The case study results with large and small network models suggest that the following an outage, wind utilization under dynamic line rating can be increased considerably if the wind power producers maintain around a 15% margin of operation.

Introduction

Network congestion is an undesirable result of insufficient capacity being available on a network to transport electricity from generation to loads. It leads to highly variable locational marginal prices (LMP) at nodes usually with high prices at load points which are affected by congestion compared to those which are not. A number of publications have used LMP as an indicator of network congestion [1–3]. In systems with large amount of wind power, network congestion hinders effective integration and utilization of wind as extra wind generated has to be curtailed thereby leading to uncertainty in revenue for wind power producers. The dynamic nature of wind results in large variations in power output over a short period of time, which makes effective utilization of wind an even bigger challenge in congested networks.

Network congestion has a greater impact in networks under contingency. When a contingency occurs in a branch, the remaining branches in the network can experience greater loading and be at a higher risk of network congestion [4–7]. While traditional security analysis uses the $N-1$ criterion this does not account for variation in output of wind leading to post contingency congestion and curtailment of wind. Therefore, even when a network seems to have no congestion and utilizes wind effectively, there is a high risk that any contingency will drastically change the situation.

A number of sources agree that the true thermal capacity of a transmission line is considerably higher than the rated values [8–12] since ratings are calculated under the worst case weather assumption although such operating conditions occurs rarely in practice. It is possible to exploit this property by using dynamic line ratings (DLR) which model the thermal limit of transmission lines as stochastically varying function of internal and external real time operating conditions such as ambient temperature, level of loading, intermittent effects, and sag. These methods capture real time variations and are an improvement over existing methods of using multiple thermal limits to account for different weather conditions based on the relationship between temperature and ampacity outlined in IEEE Std 738-2012 [13].

Some ISOs (independent system operators) currently use normal and emergency ratings as well as separate ratings for hot and cold weather. These ratings are an approximation of the real time variation in line ampacity and the actual thermal limit has a high likelihood of being significantly different. In modern power systems which consist of multiple competing entities and fast

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Nomenclature

$C_g(P_g)$	cost of conventional generation
$C_w(P_w)$	cost of wind power feed in
C_{DLR}	total cost of dynamic line rating
$C_{\mathrm{congestion}}$	total cost of network congestion
N_L	total number of branches in network
N_k	number of values in discretized probability distribution of line capacity
N_W	total number of wind generators
$(h_{pq,k}, s_{\max,pq,k})$	kth Ordered pair (probability, value) representing line capacity probability distribution
$S_{\mathrm{sch},pq}$	power flow in line from bus p to bus q
$a_{pq,k}$	the dynamic line capacity discrete probability distribution
c_{OLp}	unit cost of dynamic line rating
$P_{\mathrm{local},n}$	adjustment of load at bus n after redispatch during congestion
s_{jk}	wasted wind discrete probability distribution
t_{jk}	reserve requirement discrete probability distribution
c_D	unit cost of network congestion
LMP_i	locational marginal price at node i
$\mathrm{LMP}_{i,\mathrm{base}}$	locational marginal price at node i during uncongested base case
P_W	total wind power generation
$P_{W,\mathrm{base}}$	total wind power generation during uncongested base case
$P_{D,i}$	real power demand at bus i
LMP_V	index measuring variation in Locational Marginal Price from base case

changing power flows due to presence of intermittent renewable generation, inaccurate estimation of real time ampacity can result in underutilization of network capacity and congestion. Dynamic ratings can provide a significant increase in the normal and emergency operational flexibility of power transmission systems compared to the more traditional static rating and alleviate network congestion due to short periods of high wind power output. DLR is applicable for power systems with short to medium lines where thermal capacity as opposed to stability limit is the limiting factor to line capacity.

The benefit of DLR over conventional congestion management approaches is that it can potentially release latent capacity dynamically rather than relying on generation curtailment and demand reduction in congested parts of a network, thus improving the operational flexibility and deferring investments. Dynamic line ratings can exploit the advanced real time monitoring and control capabilities of smart grids to potentially alleviate network congestion, and ensure a more equitable allocation of costs between market participants.

The two immediate challenges of implementing the dynamic line rating methods presented in [8–11] are the need for an online, smart monitoring system to capture real time variation and the modelling of uncertainty in constraints in optimal scheduling. While uncertainty in optimization variables can be accounted for by stochastic optimization techniques, uncertainty in constraints is more challenging to model since analytical constrained optimization techniques only allow fixed constraints. Most of the power system applications of optimal scheduling problems model line power transfer limits as deterministic values and place less emphasis on dynamic variation in line capacity. An alternative to this is chance constrained optimization which allows some flexibility in the constraint satisfaction by allowing constraint violation, provided their probability is limited to a specified value [14,15].

This paper proposes a new mathematical framework and a methodology to incorporate benefits of real time variation in line ratings to temporarily relax post-outage constrained capacity of a network and to vary reinforcement thresholds. The technique allows the stochastically estimated real time ampacity to be included in scheduling decisions by allowing a degree of flexibility to satisfy dynamic thermal limit constraints. The uniqueness of the proposed approach is that it replaces the current deterministic constraints (normal and emergency) in the optimal scheduling problem, with dynamic constraints. The approach dynamically quantifies the extent to which post outage constrained capacity could be relaxed by utilizing a discrete stochastic penalty function that takes into account the merits of dynamic line ratings. This method also incorporates the benefits of smart grid environments where real time data of system parameters such as sag and ambient temperature is available. The proposed approach could potentially provide considerable advantage over traditional approaches of using deterministic ratings due to the use of real time extraction of latent capacities during the optimization process. The paper also shows how dynamic line ratings can be used to reduce the risk of post outage network congestion while better facilitating wind integration for $N-1$ and $N-2$ contingencies. The proposed technique indicates the extent of congestion in a power network by weighting LMP at each node with respect to demand and finding the difference in the weighted LMP from the uncongested base case. The extended conic quadratic (ECQ) approach presented in [16] is used for optimization. It is modified to include dynamic line ratings.

Dynamic asset rating

Stochastic optimisation with dynamic asset ratings

The maximum thermal capacity of a line depends on the maximum allowable temperature of the line at which the conductors start to lose structural integrity or undergo annealing. IEEE Std 738-2012 outlines the process for calculating the maximum ampacity based on weather conditions for steady state, transient and dynamic scenarios. A number of models [8,9,11] apply the concepts in IEEE Std. 738 to determine dynamic line ratings which use weather data as an input. Kazerooni et al. [10] have shown that when all the stochastic variations in weather are accounted for, the thermal capacity of the line can be modelled by the generalized extreme value probability distribution and in most cases the rated line capacity is on the lower end of the possible range of thermal capacities.

The correlation between wind speed and the cooling of the line was considered negligible in for this study, due the variation in weather conditions in different parts of a line [11]. While it is expected that weather conditions will mostly be favorable compared to the worst case assumptions for conventional line ratings, it is unlikely that all parts of the line will be exposed to high wind speeds which coincide with periods of high wind at the single location of the wind farm. It is assumed that the dynamic capacity is limited by regions where cooling due to wind is low and this provides a conservative estimate of the benefit due to DLR on wind integration. Typical parameters for the probability distribution of line capacity are provided in [10]. To determine the probability distribution of line ampacity historical weather data across the line