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Probabilistic pricing of ramp service in power systems with wind and solar generation

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ABSTRACT

This paper proposes a probabilistic pricing which achieves efficient operation of and investment in ramp-service providers in power systems with a large amount of wind or solar generation. The proposed pricing differs from the existing literature in that it focuses exclusively on the efficient dispatch of electrical energy with no exogenous consideration of the need for reserves or balancing services. The proposed optimal dispatch task determines both the efficient level of any preventive actions taken before a contingency event occurs and the efficient response of the power system - i.e., corrective actions - once an event occurs. We show analytically that the efficient dispatch outcome can be achieved in a decentralized market mechanism provided the market participants are profit-maximizers and price-takers. We show how the total economic benefit of an investment can be decomposed into two components (a) the normal dispatch cost benefit and (b) the economic value of the investment in contributing ramp service to the power system. In order to study different aspects of the probabilistic pricing, the IEEE 30-node example system is deliberately modified. The results show the efficiency of the proposed pricing and the use of the investment model to assess the economic value of ramp-service providers.

1. Introduction

It has long been recognized that the reliable operation of a power system requires the ability to dynamically respond to changes in supply, demand and network conditions using the available resources in the system. The actions taken by the power system operator to restore a secure operating state once a contingency has happened are known as corrective actions. The actions taken by a power system operator before a contingency has happened, to reduce the cost of corrective actions (such as procurement of balancing services) are known as preventive actions [1].

In recent years there has been a rapid increase in the penetration of variable generation resources (such as wind or solar) [2,3]. Both wind and solar generation can vary rapidly over a wide range in a manner which is, to an extent, unpredictable from one dispatch interval to the next [4,5]. This variation in production has increased the potential for large swings in the supply-demand balance [6] and has raised the question of whether the existing mechanisms for determining preventive and corrective actions are adequate [7,8]. In this paper, the ability of a power system to accommodate large swings in the supply-demand balance (either through preventive or corrective actions) is referred to as the *flexibility* of the power system.

In the absence of any particular preventive actions ex ante, the loss of a large generating unit could easily result in a supply-demand imbalance which could not be resolved within seconds even with all available ramping resources. As a result, in order to ensure power system reliability it is routine for power system operators to take preventive actions (such as setting aside sufficient fast-response resources) to ensure the power system remains in balance following the trip of a large generator. In exactly the same way, if a large movement in the output of variable generation over a somewhat longer period could not be met with all available ramping resources, the power system is said to lack sufficient flexibility. Again, the power system operator may need to take preventive actions to maintain the power system balance ex post.

Concerns regarding power system reliability and flexibility are becoming increasingly salient for power system operators [9]. In many markets with a high penetration of solar generation commentators have expressed concerns about the potential for ramp-rate constraints to bind as solar generation falls off simultaneously with the ramp up in demand to the evening peak (as in the "duck graph" from the California ISO) [10]. Reference [11] describes an event that occurred in ERCOT in 2008 in which a faster-than-expected drop-off in wind generation

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Nomenclature

Indices

$i(u)$	Existing (candidate) generator,
n	Power system node,
$l(v)$	Existing (candidate) transmission line,
t	Time period,
k	Probable contingency,

Parameters

T	Number of time periods,
$I(U)$	Number of existing (candidate) generators,
$L(V)$	Number of existing (candidate) lines,
K	Number of possible contingencies,
D_n	Demand at bus n under normal system operation,
$D_{n,k}$	Demand at bus n, in contingency k,
$RD_{i(u)}$	Ramp down rate of generator $i(u)$,
$RU_{i(u)}$	Ramp up rate of generator $i(u)$,
$GM_{i(u)}$	Minimum stable generation of generator $i(u)$,
$G_{i(u)}$	Capacity of generator $i(u)$,
$G_{i(u),k}$	Capacity of generator $i(u)$ in contingency k,
$c_{i(u)}$	Production cost of generator $i(u)$,
$c_{i(u)}^{SP}$	Start-up cost of generator $i(u)$,
$c_{i(u)}^{SD}$	Shut-down cost of generator $i(u)$,
$B_{l(v)}$	Susceptance of transmission line $l(v)$,
$F_{l(v)}$	Capacity of transmission line $l(v)$,
$F_{l(v),k}$	Capacity of transmission line $l(v)$ in contingency k,
TIC_v	Transmission investment cost for candidate line v,
GIC_u	Generation investment cost for candidate generator u,
Ξ	Suitable large constant,
r	Short term interest rate,
p_k	Probability of contingency k,
M_i	Energy limit of hydro plant i,
$Q_{i,0}$	Amount of energy stored before the operation in the reservoir of hydro generator i,
Q_i^{max}	Capacity of reservoir of hydro generator i,
η_i^g	Efficiency of pump-storage generator i,
η_i^p	Efficiency of pump-storage motor i.

Variables

x_v	Binary variable of transmission line v,
y_u	Binary variable of generator u,
$g_{i(u)}$	Dispatch of generator i (u) under normal operation,
$\hat{g}_{i(u),t,k}$	Dispatch of generator i (u) at time t for contingency k,
$g'_{i(u),k}$	Dispatch of generator i (u) after clearing of contingency k,
$f_{l(v)}$	Power flow of line l (v) under normal operation,
$\hat{f}_{l(v),t,k}$	Power flow of line l (v) at time t for contingency k,
$f'_{l(v),k}$	Power flow of line l (v) after clearing of contingency k,
θ_n	Voltage angle of node n under normal operation,
$\hat{\theta}_{n,t,k}$	Voltage angle of node n at time t for contingency k,
$\theta'_{n,k}$	Voltage angle of node n after clearing of contingency k,
$s_{i(u)}$	Start-up binary variable of generator $i(u)$ under normal operation,
$\hat{s}_{i(u),t,k}$	Start-up binary variable of generator $i(u)$ at time t for contingency k,
$s'_{i(u),k}$	Start-up binary variable of generator $i(u)$ after clearing of contingency k,
w_i	Shut-down binary variable of generator $i(u)$ under normal operation,
$\hat{w}_{i,t,k}$	Shut-down binary variable of generator $i(u)$ at time t for contingency k,
$w'_{i,k}$	Shut-down binary variable of generator $i(u)$ after clearing of contingency k,
$z_{i(u)}$	On-line or off-line binary variable of generator $i(u)$ under normal operation,
$z'_{i(u),t,k}$	On-line or off-line binary variable of generator $i(u)$ at time t for contingency k,
$\hat{z}_{i(u),k}$	On-line or off-line binary variable of generator $i(u)$ after clearing of contingency k,
Q_i	Stored water of hydro generator i,
$Q'_{i,t,k}$	Stored water of hydro generator i at time t for contingency k,
$\hat{Q}_{i,k}$	Stored water of hydro generator i after clearing of contingency k.

contributed to a rapid increase in net load (5500 MW over 1.25 h) exhausting the ramp-up capability of the available resources and forcing the system operator to invoke an emergency curtailment plan. Similar events are possible in other markets with a high degree of wind penetration. Fig. 1 shows generation in South Australia by fuel type between 22 June and 5 July 2014. Wind was the major source of generation in South Australia over this period. On 27 June 2014 at 3 a.m. wind output was 99% of native demand in South Australia and 71% of total South Australian generation. The power system operator in Australia has expressed concern that it may have insufficient resources to maintain the power system in balance if both (a) the volume of conventional synchronous generation declines further and (b) there is an outage on the interconnector with neighbouring regions [12].

Conventionally, the provision of corrective actions (such as spinning reserves or frequency control services) has been viewed as a separate, but complementary, service to the production or consumption of electrical energy. This complementary service is typically separately purchased by the system operator, often in a market mechanism which operates either alongside, or integrated with, the market for electrical energy.

This paper takes a different approach. In this paper corrective actions (reserves or balancing services) are not viewed as a separate service to the power system. Rather, the power system transacts in a single service: the production and consumption of electrical energy at different locations on the network. The volumes of energy transacted are determined using a conventional security-constrained optimal dispatch. However, the presence of inter-temporal constraints gives rise to a tension between ex ante and ex post dispatch. As we demonstrate below, even when the power system adjusts optimally to contingencies ex post it may make sense to take ex ante preventive actions in order to reduce the cost of adjustment following a contingency. In the optimal dispatch task set out below the system operator efficiently and continuously trades off the need for these preventive and corrective actions.

Furthermore, we demonstrate that private, for-profit generators, responding to price signals will voluntarily choose to set aside resources (i.e., to take preventive actions) in anticipation of the need for such resources following a contingency. This suggests that power system reliability can be handled through voluntary actions by profit-maximizing generators responding to price signals. There is no need for any separate procurement of reserves or balancing services (i.e. reserve is endogenous in our model).

The overall efficient operation of a power system involves not just efficient use of existing resources, but efficient investment in new resources over time. This paper goes on to show that private entrepreneurs, responding to price signals, will make efficient decisions regarding investment in ramp-service providers. We show how the total economic benefit of an investment can be decomposed into two