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Short-run economic dispatch with mathematical modelling of the adjustment cost ☆

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ABSTRACT

In a typical liberalised wholesale power market, an optimisation process ensures the economically efficient utilisation of the controllable resources every few minutes. But electricity networks are subject to constant shocks to the available generation, load, or transmission assets. The response to these shocks is through a variety of ad hoc mechanisms which do not involve an optimisation process and therefore cannot achieve economically efficient utilisation of the available assets. But the higher the cost of responding to contingencies ex post the greater the need there is to distort the ex ante operation of the power system. In cases where the power system cannot respond at all to a particular contingency ex post, the power system must often be operated ex ante as though the contingency has already happened. This significantly reduces the efficiency with which the available assets can be utilised ex ante. In this paper the concept of short-run economic dispatch is introduced and mathematically modelled. The concept of short-run economic dispatch is formulated through three stages: (1) the initial steady-state equilibrium, (2) transition to a new steady-state equilibrium, and (3) final steady-state equilibrium. These three stages model the state of power system before, during, and after contingency occurred. The derived mathematical model is a linear programming problem. The approach is illustrated using the IEEE 24-node example system.

1. Introduction

An efficient wholesale electricity market should use the set of available assets as efficiently as possible. On timescales of minutes or longer, efficient use of the available assets is achieved through the conventional bid-based security constrained economic dispatch. But, in a typical power system, the economic dispatch algorithm is not used over very short timescales. This is important because the need to respond to short-term shocks to the power system affects the way the power system can be operated under normal conditions, before those shocks occur. In many cases a power system operator will be required to operate the power system well within its physical limits (that is, with substantial spare unused capacity) in order to reduce the impact of potential contingencies. Furthermore, the increasing use of non-controllable generation technologies such as wind and solar has the potential to increase the size of potential contingencies, potentially further constraining the way the power system can be operated ex ante. By improving the efficiency of the operation of the power system in response to short-run contingencies, the power system can be operated more efficiently ex ante. As computing power improves it becomes increasingly possible to compute the optimal dispatch of the power system on every very short time intervals.

This paper sets out a method for computation of the optimal economic dispatch over very short timescales, allowing for both the efficient determination of the pre-contingency dispatch and the efficient post-contingency response. In brief, the proposed approach, by ensuring the least cost response to contingencies ex post, allows for the maximal efficient use of the power system ex ante. Since the cost of responding to contingencies ex post is related to the "flexibility" of the power system, we propose an index of system flexibility which is related to the extent to which the power system must be operated conservatively ex ante.

Let's explore this argument in more detail. Around the world, liberalised wholesale electricity markets routinely make use of optimisation algorithms to find the economically optimal dispatch. However, the economic dispatch algorithm is typically only ever operated over a timescale of minutes (for example, every five minutes, or every thirty minutes). This timescale is known as the 'dispatch interval'. But maintaining system security in a power system requires much faster responses – often on a timescale of seconds or less. This gives rise to a fundamental problem. While the dispatch

☆ The views expressed in this paper do not necessarily reflect the views of the ACCC or the Australian Energy Regulator.

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Nomenclature

Indexes

i	generation unit
n	bus
l	transmission line
t	time period of optimisation
k	possible contingency

The inputs to the simulation are:

ED_n	estimated load size in bus n
$\overline{G_i}$	available generation capacity of generation unit i
$\overline{P_l}$	transmission capacity of line l
M_i	energy limit of hydro power plant $i \in Nh$

Model parameters

T	time period
Δt	dispatch interval
Ng	total number of generation units
Nn	total number of buses
Nl	total number of transmission lines
Nt	total number of periods of optimisation
Nk	total number of possible contingencies
Nh	hydro power plants
$D_n, D_{n,k}$	load size in bus n before and after contingency k occurs
RR_i	ramp rate of generation unit i
c_i	production cost of generation unit i
Υ	generation connection matrix
B_l	susceptance of transmission line m
H	PTDF matrix
Φ	transmission connection matrix
ξ	fictitious cost for undelivered or overproduced energy
r	interest rate
p_k	probability of contingency k

Optimisation model variables

$G_i, \widehat{G}_{i,t,k}, G'_{i,k}$	production of unit i in the initial, transition (following contingency k), and final states
$P_l, \widehat{P}_{l,t,k}, P'_{l,k}$	power flow on line l in the initial, transition, and final states
$DC, \hat{DC}_{t,k}, DC'_k$	dispatch cost in the initial, transition, and final states
$LL_n, \hat{LL}_{n,t,k}, LL'_k$	lost load at bus n in the initial, transition, and final states
$U_n, \widehat{U}_{n,t,k}, U'_{n,k}$	undelivered load at bus n in the initial, transition, and final states
$O_i, \widehat{O}_{i,t,k}, O'_{i,k}$	over-production by unit i in the initial, transition, and final states
$\mu_n, \hat{\mu}_{n,t,k}, \mu'_{n,k}$	Lagrange multiplier of energy balance constraint for bus n in initial, transition, and final states
$\gamma_l, \hat{\gamma}_{l,t,k}, \gamma'_{l,k}$	Lagrange multiplier of flow constraint on line l in the initial, transition, and final states
$\lambda_n, \hat{\lambda}_{n,t,k}, \lambda'_{n,k}$	nodal price at bus n in the initial, transition, and final states

of the existing stock of assets is economically efficient over the time scale of the dispatch interval, over any timescale shorter than the dispatch interval, little or no attempt is made to find the economically efficient use of the available assets. The utilisation of the existing stock of assets over these timescales is therefore almost certainly economically inefficient.

However, it would be wrong to infer that a small amount of inefficiency in short-term dispatch is economically in consequential. As is well known, power systems are subject to constant shocks to the supply–demand balance. Following any contingency the power system must readjust to a new stable equilibrium. That readjustment process may involve ramping up some generation, ramping down other generation, shedding load, or some combination of all three. The greater the cost of that readjustment process, the more desirable it is to take action to restrict the operation of the power system ex ante to reduce or eliminate this cost of adjustment to a new stable equilibrium ex post. Put another way, the greater the cost of taking corrective action once a contingency occurs, the greater the value in taking protective actions ex ante. Conversely, the lower the cost of taking corrective actions (that is the greater the ability and the lower the cost of responding to a short-run disturbance), the less the need for preventive actions ex ante. Improving the efficiency of short-run dispatch increases the flexibility of the power system, reduces the cost of corrective actions, reduces the need for preventive actions, and increases the efficiency with which the power system is operated ex ante.

This point can be easily illustrated using an example. In the Australian National Electricity Market (NEM), there is a bid-based security constrained economic dispatch process which is operated every five minutes. In addition, every five minutes the dispatch engine purchases from generators the right to call on them during the dispatch interval. These additional services are known as frequency control ancillary services (FCAS) and are further divided into 'regulation' and 'contingency' services. During the dispatch interval, generators enabled for regulation service ramp up or down in response to 4-s signals from the Australian Energy Market Operator, AEMO. Otherwise, generators enabled for frequency control act autonomously, ramping up or down according to the frequency they observe. There is no centralized dispatch for intra-dispatch interval balancing.

An efficient response to a contingency, such as the outage of a transmission line, will usually involve different actions by generators and loads in different locations. Generators in some locations will typically be expected to ramp up rapidly, while other generators in other locations will be required to back off. However, since short-run dispatch in the NEM is entirely on the basis of the common system-wide frequency there is no possibility for location-based differentiation in the response of generators or loads to a short-run contingency. As a result there is no scope for efficient adjustment of the power system in response to a transmission contingency (other than the unlikely event of the complete electrical separation of part of the power system known as 'islanding'). Because the power system (as it is currently operated) cannot respond at all ex post to a transmission contingency the power system must be operated at all times with sufficient spare capacity in order to be able to handle the next-most-serious transmission outage. In practice this means that substantial spare, unutilised capacity on the transmission network must be maintained at all times. If the short-run dispatch could be improved ex post – in particular, if generators and loads could be rapidly ramped up and down by different amounts in different locations then, in principle, the power system could be operated to significantly higher limits ex ante. Put another way, if the short-run dispatch could be improved, the cost of taking corrective actions would be reduced, reducing the need for costly preventive actions ex ante. This is especially important in Australia where increasing electricity prices have recently become the subject of much political and public comment.