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Robust economic dispatch considering automatic generation control with affine recourse process

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ABSTRACT

A robust economic dispatch (ED) considering automatic generation control (AGC) with affine recourse process is proposed in this paper. The approach co-optimizes the base points and participation factors of the AGC units using preemptive goal programming and robust optimization while considering the uncertain nodal power injections and the network constraints. The proposed approach is realized by two steps. The aim of the first step is to maximize the system effective acceptable disturbance range (EADR) while minimize the generation costs and reserve costs with respect to the obtained EADR in the second step. The novelty of the approach is as follows: (a) The security of the power system is optimized by maximizing the system EADR. The approach can obtain a solution which can cover the disturbance as much as possible even when the system does not have enough adjustable capacity to cover it all. The obtained nodal EADR can quantitatively represent the anti-disturbance capability of a node. (b) The economics of the system is significantly improved by minimizing the generation costs and reserve costs while the constraint of EADR requirement is respected. (c) The conservative level of the solution can be tuned according to the user's requirements. A simplified one-step linear model is also deduced. The effectiveness and validity of the proposed approach are demonstrated by a 6-bus system, the IEEE 118-bus system, and a real 445-bus system.

Introduction

Economic dispatch (ED) [1] and automatic generation control (AGC) [2] are two important components of the intraday dispatch. ED determines the base points (BPs) of the online units with respect to the short-term load forecasting results, while AGC maintains the system frequency and/or scheduled tie-line interchanges using the area control error (ACE) singles. Generally, the time scales for ED and AGC are 5–15 min and 1–2 min respectively. By using the AGC regulation, the load changes within each ED decision interval are allocated to the online units according to the participation factors (PFs) [3].

In spite of the close relationship between ED and AGC, the control process of AGC is barely considered in the ED models. BPs and PFs are usually optimized sequentially [3,4]. Although the sequential optimization approach is easy to implement, the optimality of the solution is weakened. Ref. [5] applied AGC reserve requirement constraints to coordinate ED and AGC, and the PFs were calculated in proportion to the AGC reserve capacity of the units. However the approach cannot quantitatively reflect the relationship between the AGC reserve and system operating security. And the transmission limits are not enforced for the AGC regulation in the model, which may be unsafe in case of large power injection fluctuations.

Robust optimization (RO) is one of the most effective approaches to make decision with uncertain parameters [6]. Different from the stochastic programming (SP) [7] which has been widely applied on the unit commitment (UC) and ED problems [8–12], RO does not depend on the probability distribution functions (PDFs) of the uncertain parameters. Instead, RO can capture robust optimization results with respect to a given disturbance range by satisfying the worst case within the range. With the integration of the large scale intermittent generation resources, RO attracts more and more attentions, and it has been used in the coordination of UC and ED with uncertain injections [13–17].

Mathematically, AGC can be seen as an affine recourse [18–20] for ED since the unbalance power is allocated to the online units according to the affine function [3,4]:

$$\tilde{p}_i = p_i + \Delta\tilde{p}_i = p_i + \alpha_i \cdot \sum_{j=1}^{N_D} \Delta\tilde{d}_j \qquad (1)$$

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Nomenclature

Descriptions	in this paper, means x corresponds to the upward adjustment. Similarly, $\overset{\smile}{x}$ means x corresponds to the downward adjustment. $\tilde{x}$ means x is a random variable

Indices

i	index of the online units, $i = 1,2,\ldots,N_G$
j	index of the load nodes, $j = 1,2,\ldots,N_D$
l	index of the transmission branches, $l = 1,2,\ldots,N_L$

Random variables

$\tilde{p}_i$	generation output of the ith unit
$\Delta\tilde{d}_j$	net load disturbance at the jth node
$\Delta\tilde{p}_i$	power adjustment of the ith unit

Deterministic variables

α_i	participation factor of the ith unit. It is assumed that all the participation factors are nonnegative. α_i is 0 for the non-AGC units
p_i	base point of the ith unit
$\overset{\frown}{r}_i, \overset{\smile}{r}_i$	upward and downward AGC reserve requirements for the ith unit
$\overset{\frown}{y}_j, \overset{\smile}{y}_j$	upper limits of the effective acceptable upward/downward disturbance of the jth node
z_E, z_S	optimal values of the economic and security objective functions
$\underline{\gamma}_{jl}, \bar{\gamma}_{jl}$	introduced control variables which correspond to the worst cases of the left-hand side of (18) and (19)
$\Delta\overset{\frown}{d}{}_j^{acpt}$	upper limit of the acceptable upward disturbance of the jth node
$\Delta\overset{\smile}{d}{}_j^{acpt}$	upper limit of the acceptable downward disturbance of the jth node

Parameters

c_i	generation cost of the ith unit
$\overset{\frown}{c}_i, \overset{\smile}{c}_i$	prices of the upward/downward reserve of the ith unit
D_j	expected demand on the jth node
M_{il}	sensitivity coefficients for the power flow in the lth transmission branch with respect to the output power of the ith unit. It is commonly referred to as the generation shift factor
M_{jl}	sensitivity coefficients for the power flow in the lth transmission branch with respect to the demand of the jth node. It is commonly referred to as the load shift factor
N_D	number of the load nodes
N_G	number of the online units
N_L	number of the transmission branches
p_i^0	initial generation of the ith unit
$p_i^{\max}, p_i^{\min}$	upper and lower generation limits of the ith unit
R_i^D, R_i^U	allowed upward/downward ramp rate of the ith unit
$\overset{\frown}{R}{}_i^{\max}$	limit of the upward AGC reserve provided by the ith unit
$\overset{\smile}{R}{}_i^{\max}$	limit of the downward AGC reserve provided by the ith unit
$\underline{T}_l, \bar{T}_l$	bidirectional transmission capacity limits of the lth branch
$\Delta\overset{\frown}{d}{}_j^{load}$	maximum upward load disturbance of the jth node
$\Delta\overset{\smile}{d}{}_j^{load}$	maximum downward load disturbance of the jth node
β	an introduced parameter which is used to control the conservative level of the decision. $\beta \in [0,\ 1]$

When the BPs and PFs are determined, this affine recourse mechanism can be used to estimate the generation and transmission status of the system with respect to any realization of the random injection. This feature distinguishes the coordination of ED and AGC from that of UC and ED [13,14].

Refs. [15,20] analyze the co-optimization of ED and AGC within the RO framework. In [15], a two-stage robust ED combined with AGC is proposed. The model aims to minimize the sum of the dispatch cost, regulation capacity cost and the worst-case regulation performance cost. In [20], an affine adjustable robust OPF with renewable energy sources is proposed. The BPs of AGC units are calculated to match the forecast load and the PFs are calculated to ensure a feasible solution for the realizations of the uncertain injections within a prescribed box uncertainty set. However, the system security requirements are treated as operating constraints rather than being optimized in [15,20]. The models will have a feasible solution only if the system has enough adjustable capacity. Otherwise, the models will be infeasible and cannot give any operating suggestion to the system operators.

This paper proposes a novel robust ED approach considering AGC with affine recourse process. The system operating security and economics are optimized simultaneously considering the uncertain nodal power injections and network constraints. The approach bases on RO and preemptive goal programming (PGP) [21] which is suitable for multi-objective optimization with a strict priority order of the objectives. A simplified linear model is also deduced to facilitate the calculation. The tests of the paper are performed on the General Algebraic Modelling System (GAMS) [22]. Solvers CONOPT [23] and CPLEX [24] are selected to solve the proposed BLP and LP problems, respectively. The convergence criterion is set as 1×10^{-6}. The tests run on an Intel Core i5 personal computer with 3.2 GHz processor and 4 GB RAM. The novelty of the proposed approach is as follows;

1. The security of power system is optimized by maximizing the system effective acceptable disturbance range (EADR) in the first level of PGP. The proposed approach can obtain a solution which can cover the disturbance as much as possible even when the system does not have enough adjustable capacity. The nodal EADR can be obtained to quantitatively represent the anti-disturbance capability of the node.
2. The operating costs, i.e., the sum of the generation costs and AGC reserve costs are minimized in the second level of PGP with respect to the obtained EADR. The system operating economics can be improved significantly on the premise that the system anti-disturbance capability is not degraded.
3. A parameter referred to as guarantee ratio (GR) is introduced into the model to control the conservative level of the results. This provides a measure to tune the tradeoff between the operating security and economics.

The rest of the paper is organized as follows. In Section “Formulations of ED with AGC affine recourse”, the detailed formulation of ED considering AGC with affine recourse is described. In Section “Solution methodology based on RO and PGP”, the proposed model is transformed to a two-level deterministic bilinear programming (BLP) problem basing on the PGP and RO. Section “Case studies” gives case studies and Section “Conclusions” draws the conclusions.