Electrical Power and Energy Systems 33 (2011) 1527–1535

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Multi-area generation scheduling algorithm with regionally distributed optimal power flow using alternating direction method

K.H. Chung [a], B.H. Kim [b,1], D. Hur [c,*,2]

[a] Korea Electrotechnology Research Institute, Naeson-ro 138, Uiwang-city, Gyeonggi-province 437-808, Republic of Korea
[b] School of Electronic & Electrical Engineering, Hong-Ik University, Wowsan Rd. 85, Mapo-gu, Seoul 121-791, Republic of Korea
[c] Dept. of Electrical Engineering, Kwangwoon University, Kwangwoon Rd. 26, Nowon-gu, Seoul 139-701, Republic of Korea

ARTICLE INFO

Article history:
Received 26 July 2009
Received in revised form 3 September 2010
Accepted 23 November 2010
Available online 22 January 2011

Keywords:
Alternating direction method
Distributed optimal power flow
Generalized Benders decomposition
Generation scheduling
Interconnected power system

ABSTRACT

This paper calls attention to the core issue as to the multi-area generation scheduling algorithm in interconnected electric power systems. This algorithm consists in deciding upon on/off states of generating units and their power outputs to meet the demands of customers under the consideration of operational technical constraints and transmission networks while keeping the generation cost to a minimum. In treating the mixed integer nonlinear programming (MINLP) problem, the generalized Benders decomposition (GBD) is applied to simply decouple a primal problem into a unit commitment (UC) master problem and inter-temporal optimal power flow (OPF) sub-problems. Most prominent in this work is that the alternating direction method (ADM) is introduced to accomplish the regional decomposition that allows efficient distributed solutions of OPF. Especially, the proposed distributed scheme whose effectiveness is clearly illustrated on a numerical example can find the most economic dispatch schedule incorporated with power transactions on a short-term basis where utilities are less inclined to pool knowledge about their systems or to telemeter measured system and cost data to the common system operator and nevertheless the gains from trade such as economy interchange are vital as well.

1. Introduction

Since there is a strong possibility that utilities' profits should be vastly changeable due to the complicated interactions between generation and transmission system variables in interconnected power systems, the generation scheduling procedure will have to provide more accurate information on these interactions [1]. For the generation scheduling in interconnected power systems, it seems reasonable to make use of an integrated model of unit commitment (UC) and optimal power flow (OPF). This integrated model can definitely yield the optimal hourly operating states by taking into account the transmission system configuration which is fully reproduced by the OPF problem. Therefore, the generation scheduling problem in interconnected power systems is mathematically formulated as a large-scale mixed integer nonlinear programming (MINLP) problem which contains the continuous variables representing the power outputs and various system states at a specified instant as well as the binary variables indicating the start-up/shut-down (on/off) status of each generating unit in the course of dispatch. Unfortunately, the batch processing of the MINLP problem is highly vulnerable to divergent solutions as well as computational inefficiency. The most typical strategy for solving this MINLP problem is to use the generalized Benders decomposition (GBD) technique [2,3], which divides an original MINLP problem into a master problem consisting of binary variables and sub-problems of continuous variables by eliminating coupling constraints concerned with both binary and continuous variables. The goal is straightforward: it can enhance the computational efficiency by reducing the dimension of a MINLP problem.

This paper is intended to explore the generation scheduling algorithm based on GBD. The proposed scheme also includes the distributed OPF using regional decomposition technique which is really implemented from the alternating direction method (ADM) [4,5]. Since the alternating direction method suitable for the competitive multi-utility environment through its power transactions admits no modifications to the augmented Lagrangian function in the inter-temporal OPF separated by geographical boundaries, it is remarkably faster than any other distributed methodologies using the approximations to the augmented Lagrangian function in terms of computation speed [6].

2. Application of generalized Benders decomposition

As described in [7–10], the generation scheduling problem is mathematically defined as a large-scale MINLP problem which

* Corresponding author. Tel.: +82 31 420 6134; fax: +82 31 420 6009.
E-mail addresses: kchung@keri.re.kr (K.H. Chung), bhkim@hongik.ac.kr (B.H. Kim), dhur@kw.ac.kr (D. Hur).
[1] Tel.: +82 2 320 1462; fax: +82 2 320 1110.
[2] Tel.: +82 2 940 5473; fax: +82 2 940 5141.

0142-0615/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2010.11.013

Nomenclature

Parameters

$X_m^{off}(t)$ number of hours the generating unit m was off-line until time period t.
$X_m^{on}(t)$ number of hours the generating unit m was on-line until time period t
$D_i(t)$ load demand at bus i for time period t
$RS(t)$ spinning reserve requirement for time period t
B_{ij} susceptance of transmission line connecting bus i and bus j
L_{ij} maximum capacity of transmission line joining bus i and bus j
MDT_m minimum shut-down time of generating unit m
MUT_m minimum start-up time of generating unit m
P_m^{max} upper bound on power output of generating unit m
P_m^{min} lower bound on power output of generating unit m
SDR_m shut-down ramp rate of generating unit m
SUR_m start-up ramp rate of generating unit m
$s_m^k(t)$ constant value of variable $s_m(t)$ computed from kth iteration of unit commitment master problem

Variables and functions

$s_m(t)$ binary variable: $s_m(t) = 1$ if generating unit m is on; $s_m(t) = 0$ if not
$\xi_m^k(t)$ index for determining on/off states of generating unit m for time period t derived from inter-temporal OPF sub-problems at iteration k
$\rho_i^k(t)$ lagrange multiplier (or bus incremental cost) of bus i for time period t
$p_m(t)$ power produced by generating unit m for time period t
$\delta_i(t)$ voltage angle at bus i for time period t
TC^k total generation cost at iteration k
Z^k continuous variable which approximates fuel costs at kth iteration of unit commitment master problem
$FC_m(p_m(t))$ fuel cost of generating unit m at power output $p_m(t)$ for time period t
$SC_m(t)$ start-up cost of generating unit m for time period t

Sets

M set of all generating units
N set of all buses
T set of all dispatch time periods
K set of all iterations
Ω_i set of generating units located at bus i

gracefully deals with not merely binary variables dictating the start-up/shut-down (on/off) status of each generating unit but also continuous variables related to optimal operating states in power systems. Once the MINLP problem concurrently determines both binary and continuous variables, it may produce a solution but waste valuable computer time, which would be unacceptable to operations engineers. Worse still, the slow oscillation of successive solutions eventually deteriorates into divergence. All these unwelcome effects have to be overcome in any successful techniques, and in this context the GBD is highly reliable. When the GBD is applied to the generation scheduling problem, an original problem is totally split into a UC master problem to determine the short-term operations plans for generation resources while taking account of start-up costs and time delays and inter-temporal OPF sub-problems subject to the fixed UC schedule. The optimal dispatch solutions are accordingly created through the iterative procedures between the UC master problem and inter-temporal OPF sub-problems. The inter-temporal OPF sub-problems are computed with respect to the UC schedule derived from the master problem at the current iteration step. The Benders cuts are generated according to the results of sub-problems and then appended to the master problem at the next iteration. Here the UC master problem coordinates the turn-on and turn-off schedules of a set of electrical power generating units, depending on the Benders cuts and then gives the inter-temporal OPF sub-problems back its results. This iterative process will continue as far as the objective value of a master problem becomes at least greater than the minimum operating costs of sub-problems so far enumerated [11–14].

Obviously, this iterative procedure requires a starting UC schedule to solve its inter-temporal OPF sub-problems. As mentioned earlier, to find a combination of globally optimized generation schedule, the results deduced from inter-temporal OPF sub-problems are delivered to the UC master problem. As an initial UC schedule, we select the schedule that forces as many generators as possible to be committed among any different schedules satisfying operating constraints of sub-problems, thereby assuring the feasibility of the subproblem at the first iteration.

The simplified flowchart focusing on the application of GBD to the generation scheduling problem is vividly shown in Fig. 1.

2.1. Formulation of master problem

In a compact form, the UC master problem is described below [10]:

$$\min \quad Z^k + \sum_{t=1}^{T}\sum_{m=1}^{M} SC_m(t) \tag{1}$$

$$\text{s.t.} \quad Z^k \geqslant \sum_{t=1}^{T}\sum_{m=1}^{M}\left[s_m^k(t)\cdot FC_m(p_m^k(t))\right] + \sum_{t=1}^{T}\sum_{m=1}^{M}\left[\xi_m^k(t)\cdot\left(s_m(t)-s_m^k(t)\right)\right] \text{for} \quad \forall\, k\in K \tag{2}$$

$$\sum_{m=1}^{M}\left(s_m(t)\cdot P_m^{max}\right) \geqslant \sum_{i=1}^{N} D_i(t) + RS(t) \quad \text{for} \quad \forall\, t\in T \tag{3}$$

$$\sum_{m=1}^{M}\left(s_m(t)\cdot P_m^{min}\right) \leqslant \sum_{i=1}^{N} D_i(t) + RS(t) \quad \text{for} \quad \forall\, t\in T \tag{4}$$

$$(X_m^{on}(t-1)-\mathrm{MUT}_m)\cdot(s_m(t-1)-s_m(t)) \geqslant 0 \quad \text{for} \quad \forall\, m\in M, \forall\, t\in T \tag{5}$$

$$(X_m^{off}(t-1)-\mathrm{MDT}_m)\cdot(s_m(t)-s_m(t-1)) \geqslant 0 \quad \text{for} \quad \forall\, m\in M, \quad \forall\, t\in T \tag{6}$$

The Benders cuts of (2) serve to constrain the feasible region to a relatively small solution space of a master problem so that total generation cost in the master problem can be less than that inferred from the inter-temporal OPF sub-problems. In (2), the index $\xi_m^k(t)$ is concisely written as follows:

$$\xi_m^k(t) = \begin{cases} FC_m(P_m^k(t)) - \rho_i^k(t)\cdot P_m^k(t) & ifs_m^k(t)=1 \\ FC_m(P_m^{min}) - \rho_i^k(t)\cdot P_m^{min} & ifs_m^k(t)=0 \end{cases} \quad \text{for} \quad \forall\, m\in\Omega_i \tag{7}$$

Evidently, the transmission network is included in deciding on/off states of generating units by adopting the index of (7) where bus incremental costs incurred by transmission capacity limits of