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A scenario-based multiobjective operation of electricity markets enhancing transient stability

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ABSTRACT

Electricity market clearing is currently done using deterministic values of power system parameters considering a fixed network configuration. This paper presents a new day-ahead joint market clearing framework (including energy, spinning reserve and non-spinning reserve auctions), which considers dynamic security of power system in the market clearing. The proposed framework has a stochastic multiobjective model considering power system uncertainties. It consists of three stages. Firstly, the uncertainty sources, i.e. contingencies of generating units and branches, are modeled using the Monte Carlo simulation (MCS) method. Subsequently, in the second stage, the proposed multiobjective framework simultaneously optimizes competing objective functions of offer cost and dynamic security index, i.e. corrected transient energy margin (CTEM). This index is selected because of useful linearity properties which it posses based on the sensitivity of the CTEM with respect to power shift between generators. The optimization problem in the second stage takes DC power flow constraints and system reserve requirements into account. Finally, in the last stage, scenario aggregation based on the expected value of the decision variables produces the final results of the market clearing framework. The 10-machine New England test system is studied to demonstrate effectiveness of the proposed stochastic multiobjective market clearing scheme.

1. Introduction

Recent major blackouts in North America and Europe [1] have rekindled the security requirements of power systems, an important matter that has been regretfully neglected in favor of more financial concerns in recent years. This renewed interest calls also for research on electricity markets with more secure solutions. Conventional market clearing schemes may not provide sufficient security level to find a more economical solution. In as much as market clearing is a mathematical optimization problem satisfying a set of constraints, some variables will hit their limits. For instance, a few branches can be fully loaded; or, some voltages can be set at their lower limit; or, the generation of critical generators can be increased. Although there is no violation, the system may be vulnerable against disturbances. In other words, the stability margin of the network may be low after some contingencies. In such a network, if any potential instability due to a prospective contingency is expected especially in the vulnerable areas of the network, some preventive actions, e.g. load shedding or startup of new units, have to be done to retain the system security [2]. Therefore, it is essential to mitigate critical contingencies by means of a method so that the security margin of the network is retained.

The power system security problems are classified as static and dynamic. The static security problem implies evaluating the system steady state performance for all possible contingencies. This means neglecting the transient behavior and any other time-dependent variations due to load-generation conditions. The dynamic analysis of security evaluates the time-dependent transition from the pre-contingent state to the post-contingent state. Dynamic security has been analyzed either by deriving dynamic security functions only, or along with the development of some preventive action techniques [3–4]. In the new structure, the static security is usually measured through "system congestion" levels, which have a direct effect on market transactions and energy prices. Thus, when the system is deemed congested, operators must take corrective actions (e.g. the fast re-dispatching of generation or the curtailment of selected loads under a specific contingency) to maintain certain allowed system security levels, which usually result in curtailment of power transactions and increased prices for most market participants [5]. In most literatures, it is assumed that deployment of enough reserves on the remaining units is sufficient to restore the normal situation. In [6–8], security-constrained models including the line flow constraints with pre-specified nodal or area reserves, concerning static security, are considered. Also, Arroyo and Galiana [9]

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Nomenclature

i, j	indices of bus
s	index of scenario
NB	number of system buses
NS	number of scenarios of the scenario generation stage after scenario reduction
k	index for Pareto optimal solution
N	number of PV buses
M	number of Pareto optimal solutions
n	number of credible contingencies
$\tilde{\omega}_i$	angular velocity of the rotor of the ith machine
M_i	inertia constant of machine
M_T	$M_1 + M_2 + \cdots + M_n$
P_{mi}	mechanical power input of the ith machine
P_{ei}	electrical power output of the ith machine.
$V_{KE}(\tilde{\omega})$	transient kinetic energy (TKE) function
$V_{PE}(\theta)$	transient potential energy (TPE) function
θ_i^{sp}	the angle of *stable equilibrium point* (SEP) of the ith machine for the post-fault power system
p	superscript for post fault system
SF_j	the sensitivity of CTEM with respect to the generation of unit j (P_{Gj})
$CTEM_0$	the network CTEM at the base case
$CTEM_j$	the system CTEM after a little change ΔP_{Gj} in the generation of the unit j with respect to the base case
π_s	probability of the *sth* scenario
π_s^{norm}	normalized probability of the sth scenario
FOR_i^G	forced outage rate of the unit located in the ith bus
$FOR_{i,j}^B$	forced outage rate of branch between ith and jth buses
$w_{i,s}^G$	status of the unit located in the ith bus in the sth scenario obtained from MCS in the scenario generation stage (forced outage state or available)
$w_{i,j,s}^B$	status of branch between ith and jth buses in the sth scenario obtained from MCS in the scenario generation stage (forced outage state or available)
z_i	a binary variable indicating that the unit located in the ith bus accepted or not in the energy market
P_{Di}	active load located at the ith bus
P_{Gi}	energy output of the unit located in the ith bus of the joint market
$SR_{i,s}^{up}$ and $SR_{i,s}^{dn}$	capacity assigned to up and down spinning reserves for the unit located in the ith bus in the sth scenario, respectively
$NSR_{i,s}$	capacity assigned to non-spinning reserve for the unit located in the ith bus in the sth scenario
ρ_i^e	bid price of the unit located in the ith bus for energy
ρ_i^{SRup} and ρ_i^{SRdn}	bid price of the unit located in the ith bus for up and down spinning reserves, respectively
ρ_i^{NSR}	bid price of the unit located in the of ith bus for non-spinning reserve
$P_{G\max,i}$ and $P_{G\min,i}$	upper and lower limits of active power of the unit located in the ith bus, respectively
$SR_{\max i}^{up}$ and $SR_{\max i}^{dn}$	maximum up/down response rate limited spinning reserve of the unit located in the ith bus, respectively
$NSR_{\max i}$	maximum response rate limited non-spinning reserve of the unit located in the ith bus
$\lvert S_{ij,s}\rvert$	apparent power flow of the branch between ith and jth bus in the sth scenario
$\lvert \bar{S}_{ij}$	apparent power flow capacity of the branch between ith and jth bus

proposed a formulation for market clearing process in the form of an optimization problem that accounts for transmission flow limits (using DC load flow) and two types of reserves offered by both generators and loads. In [10], a multiobjective approach based on interior point method is used in an optimal power flow, so that the social benefit and the distance to a maximum loading condition are maximized at the same time. However, their work is based on a static analysis framework and reserve services are not considered. On the subject of static security analysis, nonlinear optimization techniques have also been used to address a variety of voltage stability issues, such as the maximization of the loading parameter in voltage collapse studies, as discussed in [11–13]. However, considering static security cannot guarantee global security of a power system. While the steady state operating points of power system are deemed secure, its stability margins may severely decrease along the transition path of a contingency and even the power system may lose its stability in the transition period. Many research works have discussed about this matter and indicated the importance of dynamic security issues in the security studies of power systems [14–16]. On the other hand, dynamic security constrained dispatch of an electric power network is a challenging task. Particularly in the deregulated framework where generation, transmission, and distribution are separated entities, generation dispatch when dynamic security concerns have to be taken into account is a more complicated task [17].

Dynamic security assessment methods can be classified in three categories: time-domain simulation [18], transient energy function (TEF) methods [19,20], and single machine equivalent techniques [21,22]. Results of time-domain method are the most accurate and reliable ones with respect to other methods. However, time-domain method was proven to be slow because they require numerical integration of large families of dynamic equations. Moreover, they do not provide any information about the degree of stability (or instability) of the system [23]. On the other hand, the main advantages of the TEF approach are computational speed and the ability of providing a security margin or index to evaluate the degree of stability. However, the method sometimes fails to yield a practical result because of non-convergence problems encountered in attempting to compute the relevant "unstable equilibrium point," especially in the case of stressed systems [23]. This shortcoming has been overcome in the hybrid approach which combines time-domain simulation and transient energy analysis [24]. First, time-domain integration is performed and then a TEM is estimated as the system stability index. However, in [23] it has been shown that the hybrid approach may lead to unreliable results in evaluating control tools for stability enhancement. To remedy this problem, the corrected hybrid method combining time-domain simulation and corrected transient energy function (CTEF) has been proposed [23–27]. The CTEF is really a method for computing a stability index called the corrected transient energy margin (CTEM). An important feature of the CTEM is that it bears a linear relationship, within a usable range, to important control variables such as generator power exchanges [23–27]. A brief description of CTEF and CTEM will be introduced in the next section.

Under deregulation, there are many uncertainties in the power system related to, e.g., electrical load variations and generator and branch outages. The stochastic modeling of electricity contracts