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An implementation of particle swarm optimization to evaluate optimal under-voltage load shedding in competitive electricity markets

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HIGHLIGHTS

- Under-voltage load shedding in a reregulated power system is investigated.
- A technoeconomic multi-objective optimization is proposed.
- Social welfare is considered in the proposed method.
- PSO is utilized for determining an optimal load shedding scheme.
- A significant performance of the proposed method is achieved.

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ABSTRACT

Load shedding is a crucial issue in power systems especially under restructured electricity environment. Market-driven load shedding in reregulated power systems associated with security as well as reliability is investigated in this paper. A technoeconomic multi-objective function is introduced to reveal an optimal load shedding scheme considering maximum social welfare. The proposed optimization problem includes maximum *GENCO*s and loads' profits as well as maximum loadability limit under normal and contingency conditions. Particle swarm optimization (PSO) as a heuristic optimization technique, is utilized to find an optimal load shedding scheme. In a market-driven structure, generators offer their bidding blocks while the dispatchable loads will bid their price-responsive demands. An independent system operator (ISO) derives a market clearing price (MCP) while rescheduling the amount of generating power in both pre-contingency and post-contingency conditions. The proposed methodology is developed on a 3-bus system and then is applied to a modified IEEE 30-bus test system. The obtained results show the effectiveness of the proposed methodology in implementing the optimal load shedding satisfying social welfare by maintaining voltage stability margin (VSM) through technoeconomic analyses.

1. Introduction

Power systems secure and economic operation in a restructured environment involves: a balance between generation and load, service continuation, stability of power system through social welfare maximization. Any disturbance in a power system like generator or line contingency or a sudden increase in load demand leads to insecure operation while it may cause voltage instability. Voltage stability is considered as the ability of a power system to maintain steady voltages at all load buses under normal operating conditions and after occurring a disturbance [1]. Two well-known methods for maintaining voltage stability are: preventive and corrective actions. Preventive actions are performed based upon pre-contingency state through applying required control strategies to provide a satisfactory security margin. Corrective actions are required when a severe disturbance is imposed on the system and tries to return the system within its security margin. A power system might be in normal, alert, emergency, in extremis and restorative states. Load curtailment can be applied when the system is in the emergency state while load shedding is employed when the system is in extremis state and is driven to collapse [2]. When all other control procedures are unable

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Nomenclature

n_B	number of buses
n_G	number of *GENCO*s
n_{line}	number of lines
n_{load}	number of loads
N_{Gn}	number of generators of n_{th} *GENCO*
λ_i	*LMP* of bus i (\$ MWh^{-1})
a_m, b_m, c_m	generation cost coefficients
α_m, β_m	strategic variables
ρ_m	bidding block price
α_i^k	load importance factor at bus i for load type k
$C_{cong,ij}$	congestion rent of branch ij (\$ h^{-1})
C_{GENCO}	*GENCO*'s cost (\$ h^{-1})
C_{EPNS}	cost of expected power not supplied (\$ h^{-1})
R_{GENCO}	*GENCO*'s revenue (\$ h^{-1})
P_{sys}	maximum loadability limit of system (MW)
n	index of normal state
c	index of contingency state
w	weighting factor
P_{ij}	power flow of line ij (MW)
$P_{G,i}^c$	active power generation in contingency state at bus i (MW)
$P_{D,i}^c$	real power demand in contingency state at bus i (MW)
$\Delta P_{D,i}^c$	amount of load active power shed at bus i (MW)
V_i^c	bus voltage in contingency state at bus i (V)
Y_{ij}	admittance of line ij (Ω)
θ_{ij}	admittance angle of line ij
δ_i^c	voltage angle at bus i in contingency state
$Q_{G,i}^c$	reactive power generation in contingency state at bus i (MVAr)
$Q_{D,i}^c$	load reactive power in contingency state at bus i (MVAr)
$\Delta Q_{D,i}^c$	amount of load reactive power shed at bus i (MVAr)
$P_{G,i}^{\min}$	minimum active power generation at bus i (MW)
$P_{G,i}^{\max}$	maximum active power generation at bus i (MW)
$Q_{G,i}^{\min}$	minimum reactive power generation at bus i (MVAr)
$Q_{G,i}^{\max}$	maximum reactive power generation at bus i (MVAr)
$P_{D,i}^{\min}$	minimum amount of load to be supplied at bus i (MW)
$P_{D,i}^n$	real power demand in normal state at bus i (MW)
S_{ij}^c	apparent power flow of line ij in contingency state (MVA)
$S_{ij}^{\max}$	apparent power limit of line ij (MVA)
$V_i^{\min}$	lower limit of voltage at bus i (V)
$V_i^{\max}$	upper limit of voltage at bus i (V)

to maintain power system security in the case of a disturbance or contingency, optimal load shedding (OLS) will be utilized as the last resort to prevent system blackout [3]. Load shedding (LS) is generally categorized in two well-known methodologies: under-frequency load shedding (UFLS) and under-voltage load shedding (UVLS). UFLS or UVLS is performed when the frequency or voltage falls below a specified threshold. The load shedding procedure cuts a particular amount of load in such a manner that a balance between generation and demand is achieved resulting in a widespread system blackout prevention [4]. The main factors in load shedding are: location, amount, and time of load cut. On the other hand, to prevent post-contingency problems, the location of the proposed buses for load shedding must be determined based upon the load importance, curtailment cost and the distance of the curtailed load to the contingency location [5].

Load shedding implementation can be categorized into three main procedures [6–9]. The first procedure involves shedding a fixed amount of load which is similar to UFLS [10]. This procedure involves time simulation analysis and studying instability from dynamic aspects of a power system while a drawback of such approach is integrating a time domain simulation to an optimization problem [11]. The second approach considers shedding an amount of load with dynamic characteristics which involves a precise modeling of dynamic load parameters. The third approach utilizes optimal power flow (OPF) equations of a power system static model to determine the minimum load shedding. Since the dynamics associated with voltage stability are often slow, a static approach proposes a good approximation of system voltage stability. The fundamental idea of such approach is finding a feasible solution to the power flow equations [12,13]. Load shedding considering static model of a power system is addressed in former researches and is solved using different mathematical techniques such as linear programming (LP), nonlinear programming, and interior point method [14–16]. In some other studies, evolutionary algorithms such as genetic algorithm (GA) [17], particle swarm optimization (PSO) [6–9], and ant colony optimization (ACO) [18] have been utilized to tackle the load shedding problem. The advantage of the evolutionary algorithms is their accuracy in obtaining feasible solution while considering problem constraints. In Ref. [9], an approach for UVLS is presented based upon a dynamic security-constrained OPF utilizing PSO. It is aimed to provide sufficient voltage stability margin for post-contingency condition. Load shedding as a solution for congestion management along with generation rescheduling is presented in Ref. [19], where a multi-objective PSO method is suggested to solve such a complex nonlinear problem. Minimum load shedding has been developed using conventional PSO and coordinated aggregation based PSO (CAPSO) in Ref. [20]. The previous studies have conducted the optimal load shedding in a regulated market environment where no competition is considered for market participants.

However, in the reregulated power market, beside the secure operation as the main purpose, the profit of market participants such as: *GENCO*s, TRANSCO and customers should be maximized. In fact, the role of ISO is to maximize social welfare through optimizing all participants' profit considering operational constraints. In a market-driven environment, the locational marginal prices (*LMP*s) are determined according to the *GENCO*s' offers and real power losses as well as lines congestion. When a generator contingency occurs, *GENCO*s are obliged to pay the penalty of load shedding which is in terms of expected power not supplied (*EPNS*). On the other hand, congestion influence on market clearing price (MCP) which may lead to locational marginal price (*LMP*) differences. Congestion rent is defined as the difference of *LMP*s multiplied by the power flow through a congested line [21–23].

This paper addresses a steady state load shedding scheme where a multi-objective function to optimize a technoeconomic model in a restructured power system environment is considered. In the proposed methodology, an optimal load shedding is handled through optimizing technoeconomic social welfare including: *GENCO*s and customers profits, congestion rent, and loadability limit. Here, the smart market procedure is utilized where the ISO as the market authority receives *GENCO*s' offers and dispatchable loads bidding blocks to establish the market clearing price and to determine the generating pattern as well as the participation amount of dispatchable loads. In the proposed scheme when a contingency occurs, the minimum load shed that may guarantee the social welfare will be obtained.

The rest of this paper is organized as follows. Section 2 elaborates a framework of the proposed scheme through a 3-bus system.