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A novel multi-zone reactive power market settlement model: A pareto-optimization approach

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ABSTRACT

This paper presents a Pareto-optimization based zonal day-ahead reactive power market settlement model named as multi-zone DA-RPMS model. Three competing objective functions such as Total Payment Function (TPF) for reactive power support services from generators/synchronous condensers, Total Real Transmission Loss (TRTL) and Voltage Stability Enhancement Index (VSEI) are optimized simultaneously by satisfying various power system operating constraints while settling the day-ahead reactive power market. The proposed multi-zone DA-RPMS model is tested and compared with single-zone DA-RPMS model on standard IEEE 24 bus reliability test system. A Hybrid Fuzzy Multi-Objective Evolutionary Algorithm (HFMOEA) approach is applied and compared with NSGA-II for solving these DA-RPMS models in competitive electricity market environment. Further, both the single-zone and multi-zone DA-RPMS models are also analyzed on the basis of market power owned by any generator/any generating company. The simulation results obtained confirm the superiority of HFMOEA in finding the better Pareto-optimal fronts in order to take better day-ahead reactive power market settlement decisions.

1. Introduction

Of late, an appropriate reactive power provision has been one of the major concerns by the Independent System Operator (ISO) in order to maintain the reliable, economical and secure power system operations in deregulated environment. Unlike the real power, reactive power does not accomplish useful work (e.g., runs motors and lights lamps) but it is necessary to improve the capability to transfer bulk Alternating Current (AC) power over transmission lines. Moreover, it is responsible to establish and maintain electric and magnetic fields in ac equipment. Therefore, reactive power is not only necessary to operate the transmission system reliably, but it can also substantially improve the efficiency with which real power is delivered to customers. Increasing reactive power production at certain locations (usually near a load center) can sometimes alleviate transmission constraints and allow cheaper real power to be delivered into a load pocket. The detailed analysis of characteristics, its urgent needs and pricing of reactive power issues are presented in the report submitted by Federal Energy Regulatory Commission (FERC) [1]. This report also summarizes many conceptual aspects and current practices, points out various deficiencies in the reactive power procurement in the US markets and provides recommendations for, and lists a number of challenges in the reactive power supply and its usage area. Furthermore, reactive power is tightly coupled with bus voltages throughout the power system, and hence it has a significant effect on system security. In fact, inadequate reactive power led to voltage collapses and has been a main cause of major power outages across the world in the past. Now, it has been a well established fact that there is a need of proper management of reactive power as one of the six ancillary services which must be provided through the competition in electricity markets [1]. The strongly local nature of reactive power restricts its ability to be transmitted over electrically large distances. More importantly, such characteristics imply that reactive power cannot be treated as a commodity of the same type as active power or active energy. Therefore, it renders the economics of reactive power and voltage support to be challenging and makes highly questionable the feasibility of setting up a workable market structure for reactive power provision. Transparent market processes and efficient market clearing mechanisms are needed for achieving optimal reactive power management in competitive electricity market. Hence, the literature review presented in subsequent paragraphs is focused on recent developments of reactive power market models and market clearing schemes along with their solution techniques.

Initially, the research efforts were made in order to develop an optimal pricing scheme for reactive power provision using

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Nomenclature

Abbreviation

TPF	total power payment function ($)
TRTL	total real transmission loss (MW)
VSEI	voltage stability enhancement index (L-index)
ρ_0	uniform availability price ($/MVAr-h)
ρ_1	uniform cost of loss prices for absorbing reactive power ($/MVAr-h)
ρ_2	uniform cost of loss prices for producing reactive power ($/MVAr-h)
ρ_3	Uniform opportunity price ($/MVAr-h)/MVAr-h
$a_{0,i}$	cost of availability price offer (in $)
$m_{1,i}$	cost of loss component price offer for operating in under excited mode (absorb reactive power), $Q_{G\mathrm{min},i} \le Q_{G,i} \le 0$ (in $/MVAr-h),
$m_{2,i}$	cost of loss component price offer for operating in the region $Q_{\mathrm{Gbase},i} \le Q_{G,i} \le Q_{GA,i}$ (in $/MVAr-h)
$m_{3,i}$	cost of lost opportunity price offer for operating in the region $Q_{\mathrm{GA},i} \le Q_{\mathrm{G},i} \le Q_{\mathrm{GB},i}$in ($/MVAr-h)/MVAr-h
$W_{0,i}$, $W_{1,i}$, $W_{2,i}$ and $W_{3,i}$	binary variables associated with *i*th generator
$Q_{\mathrm{G1},i}$, $Q_{\mathrm{G2},i}$ $Q_{\mathrm{G3},i}$ and $Q_{\mathrm{A},i}$	reactive power output of *i*th generator in the region $(Q_{\mathrm{Gmin}},0)$,$(Q_{\mathrm{Gbase}},Q_{GA})$,$(Q_{\mathrm{GA}},Q_{\mathrm{GB}})$ and$(0,Q_{\mathrm{Gbase}})$, respectively
$P_{k,\mathrm{loss}}$	real power loss in *k*th transmission line
$P_{\mathrm{G},i}$,$P_{\mathrm{D},i}$	real power generation and demand at *i*th bus
$Q_{\mathrm{G},i}$,$Q_{\mathrm{D},i}$	reactive power generation and demand at *i*th bus
$Q_{G\mathrm{min},i}$,$Q_{G\mathrm{max},i}$	minimum, maximum limits of reactive power generation and demand
$Q_{\mathrm{C},i}$	shunt capacitor/indictor at *i*th bus
$Q_{\mathrm{Cmin},i}$,$Q_{\mathrm{Cmax},i}$	minimum, maximum values of shunt capacitor/inductor at *i*th bus
S_l,$S_l^{\max}$	power flow and its maximum value at *l*th transmission line
g_k	conductance of *k*th transmission line
G_{ij}	transfer conductance between *i*th and *j*th bus (p.u.)
B_{ij}	transfer susceptance between *i*th and *j*th bus (p.u.)
θ_{ij}	voltage angle difference between buses and (radian)
V_i	voltage at *i*th bus (p.u.)
$V_i^{\min}, V_i^{\max}$	minimum, maximum limits of voltage at *i*th bus (p.u.)
T_k	transformer tap setting at *k*th transmission line (p.u.)
$T_k^{\min}, T_k^{\max}$	minimum, maximum limits of transformer tap setting at *k*th transmission line (p.u.)
N_{B}	total numbers of buses
N_i	total of numbers of buses adjacent to *i*th bus, including *i*th bus
N_{PV}	total number of generator buses
N_{PQ}	total number of load buses
N_{L}	total number of transmission lines
N_{T}	total number of transformer taps
N_{C}	total number of shunt capacitors/inductors
N_{Z}	total number of VCAs/zones formed in the power system
$V_{\mathrm{t},i}$	terminal voltage of *i*th generator
$I_{\mathrm{a},i}$	steady state armature current of *i*th generator
$E_{\mathrm{af},i}$	armature e.m.f. generated of *i*th generator
$X_{\mathrm{s},i}$	synchronous reactance of *i*th generator
$P_{\mathrm{GR},i}$	rated real power output of *i*th generator

conventional marginal price theory [2–4] with having an assumption that all consumers should pay and all producers are remunerated for reactive power services. A market model process to manage reactive services by independent transmission operators is presented in [5]. It used a piece-wise linear representation of the capability curve of each generator for computing reactive power cost curves. In reference [6], a two-step approach for reactive power procurement is proposed. In first step, the marginal benefit of each reactive power bid with respect to total system losses is determined, and in second step, an OPF-based model maximizing a social welfare function is solved to determine the optimal reactive power procurement. This work is further extended in reference [7], where a uniform price auction model was proposed to competitively determine the prices for different components of reactive power services namely: availability, operation and opportunity. Market clearing was achieved by simultaneously minimizing of payment, total system losses, and deviations from contracted transactions using compromise programming approach. Mainly, a problem of market power (some of the reactive power producers misusing the situation by giving by extraordinary high prices of their services) may arise while establishing reactive power market for voltage control ancillary services [8]. This problem is caused due to local nature of reactive power and voltage phenomenon in electrical networks. Therefore, a need of effective design of localized/zonal reactive power market considering Voltage Control Areas (VCAs) is realized to overcome the same problem. In [8], a localized or zonal reactive power market is proposed using the concept of VCAs/zones in which the reactive power market is settled by calculating the zonal uniform market clearing prices.

However, seasonal market for reactive power encounters couple of problems [9]. Firstly, the reactive power consumption of system is volatile that its forecasting over a season becomes very hard. Secondly, the reactive power requirement of system strongly depends on the loading condition of network. Some of the recent publications [9–12] advocated a day-ahead reactive power market instead of long-term reactive market. In reference [10], a pay-as-bid based reactive power market clearing scheme is presented which implicitly considers the local nature of reactive power during the clearing of reactive power market. The uncertainty of generating units in the form of system contingencies is considered in the market clearing procedure by the stochastic model [11,12]. In all these reactive power market models, the Reactive Power Market Clearing (RPMC) problem is formulated as single objective optimization problems.

In recent years, all real world optimization problems are being tried to be formulated in multi-objective optimization framework, in which multiple objective functions are optimized simultaneously. In fact, these objective functions are non-commensurable and often conflicting objectives. Multi-objective Optimization Problems (MOPs) with such conflicting objective functions give rise to a set of optimal solutions, instead of one optimal solution, called as Pareto-optimal solutions [13]. Therefore, in a multi-objective optimization framework, the main aim is to find out a set of feasible and non-dominating solutions which forms a Pareto-optimal front within the entire search space. Many multi-objective reactive power optimization problems such as Optimal Reactive Power Dispatch (ORPD) [14–18] and RPMC [19,20] are formulated as MOPs and several Multi-Objective Evolutionary