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Scenario-based stochastic framework for coupled active and reactive power market in smart distribution systems with demand response programs

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ABSTRACT

In this paper, an efficient stochastic framework is proposed to develop a coupled active and reactive market in smart distribution systems. Distributed Energy Resources (DERs) can offer active powers to the market and also offer their reactive powers via a multi-component bidding framework constructed based on their reactive power capability diagrams. Distribution Company (Disco) buys active and reactive powers from a wholesale market and sells them via this market. Aggregators on behalf of responsive loads can participate in the market using a demand buyback program (DBP). The uncertainties of forecasted loads and wind power generation are considered in the proposed framework. To model the stochastic variables, the scenario tree is created using the Weibull and the Gaussian probability density functions (PDFs). The cost objective function of the stochastic coupled market clearing consists of the expected costs of energy and reactive power purchased from the DERs and Disco, the expected penalty cost of CO_2 emissions of DERs and the main grid as well as the expected cost of running DBP. The proposed market is cleared through a mixed-integer nonlinear optimization problem solved in GAMS software. The effectiveness of the proposed method is investigated based on a 22-bus 20-kV radial distribution test system.

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1. Introduction

1.1. Literature review and motivation

Recently, economic and environmental concerns, as well as the need for the more reliable and flexible power systems are playing a key role to promote the concept of smart grid. In order to support this idea, there is an international movement supporting the development of Distributed Energy Resources (DERs) for electricity generation and the promotion of pollutant emissions limits. On the other hand, uncoordinated utilization of the DERs may have destructive effects on reliable and secure operation of the power systems and on power quality indices [1].

In all electric distribution systems, it is necessary that the voltages at all points along the distribution feeders under all loading conditions remain within an acceptable range. This is an essential operating requirement and is addressed as Volt-VAr control (VVC) in order to optimally determine dispatch schedules of all switchable capacitors, the tap settings of transformers and reactive power outputs of DERs. Due to the ability of Distributed Generations (DGs) to produce and absorb reactive power, they can efficiently participate in the VVC. In the literature, the VVC is categorized into two main categories: centralized offline control and real-time control methods [1]. In the first category, the VVC equipment is optimally scheduled based on forecasted demands. A two-stage model has been proposed in Ref. [2] for daily VVC of distribution systems including DERs and considering environmental and economic aspects. In Ref. [3], an optimization algorithm based on a Chaotic Improved Honey Bee Mating Optimization (CIHBMO) has been utilized for multi-objective daily VVC in distribution systems with DGs. In Ref. [4], a fuzzy adaptive particle swarm optimization algorithm has been implemented to solve the price-based daily VVC problem in distribution systems including

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Nomenclature

NWT/NDG total number of WTs (DGs)
$NBus$ total number of buses
Na total number of aggregators
Npl_m total number of participated loads through aggregator mth
V_t voltage at terminal bus of a DG
V_g voltage at the grid connection point of a WT
$V_{i,s}$ voltage of bus i at scenario s
E^{max} maximum internal voltage of synchronous machine
S_{DG}^{rated} nominal apparent power of the DG
I_c (V_c) converter's current (voltage) of the WT
$P_{DG,i,s}/P_{WT,i,s}/P_{Disco,s}$ cleared active power of the ith DG/ith WT/Disco at scenario s
$Q_{DG,i,s}/Q_{WT,i,s}/Q_{Disco,s}$ scheduled reactive power of ith DG/ith WT/Disco at scenario s
Q_{DG}^{mnd} maximum mandatory reactive power produced by the DG
Q_{WT}^{mnd} maximum mandatory reactive power produced by the WT
$\pi_{DG,i}/\ \pi_{WT,i}\ /\ \pi_{Disco}$ offered price of electrical energy by the ith DG/ith WT/Disco
$CO_{2,Disco}$ CO_2 emissions related to Disco (considered as the main grid) (ton/MW)
$CO_{2,DG,i}\ /\ CO_{2,WT,i}$ CO_2 emissions from the ith DG/ith WT (ton/MW)
$CO_{2,cap}$ permissible CO_2 emissions (ton/MW)
$CS_{m,i}$ set of customers of aggregator mth which is at bus ith
EPC_{CO2} CO_2 emission penalty cost ($/ton)
$P_{Disco}^{max}/P_{DG,i}^{max}$ maximum active power bid quantity offered by Disco/ith DG
$P_{WT,i,s}^{available}$ available active power output of ith WT at scenario s
P_{WT}^{rated} rated active power of WT
Tap_s tap position of on-load tap changer at scenario s
$Tap_{min}(Tap_{\max})$ minimum (maximum) tap position of on-load tap changer
$CStep_{i,s}$ step position of ith switched shunt capacitor at scenario s
$CStep_i^{min}(CStep_i^{max})$ minimum (maximum) step of ith switched shunt capacitor
$\rho_{Q,Disco}$ reactive bid price offered by Disco
$P_{G,i,s}(P_{D,i,s})$ generated (consumed) active power at bus i at scenario s
$Q_{G,i,s}(Q_{D,i,s})$ generated or absorbed (consumed) reactive power at bus i scenario s
$DR_{m,i,s}$ activated response of participated load at node ith of aggregator mth at scenario s
$DRP_{m,i,s}$ demand response potential offered by the aggregator mth for its participated load at node ith at scenario s
$DRPB_{m,i}$ demand response price bid of load at node ith of aggregator mth
X_s reactance of synchronous machine based DG

DGs. A cost-based joint active and reactive power scheduling method has been presented in Ref. [5] for the coordinated VVC issue in smart distribution systems. In Ref. [6], combined analytic hierarchy process technique and binary ant colony optimization method have been adopted as a solution methodology to solve a multi-objective daily VVC. In the second category, the voltage control devices are optimally scheduled in real time and hence it is executed in automated distribution systems [7]. By extending Supervisory Control and Data Acquisition (SCADA) capabilities based on the communication infrastructure, Remote Terminal Units (RTUs) are extensively implemented throughout the modern distribution systems [8–10]. Based on these capabilities, authors in Ref. [8] have introduced a real-time control method for improvement of voltage regulators in distribution feeders including DGs. In Refs. [9,10], real time reactive power control models have been presented to optimally control switchable capacitors at distribution level aiming at minimizing the total power losses and maintaining an admissible voltage profile.

So far, the reactive power markets at wholesale level have been investigated by many researchers [11–16]. In these markets, synchronous generators usually provide reactive power ancillary service and they offer their reactive power via various bidding structures to the market. In Ref. [11], a quadratic cost model for reactive power has been used to optimize reactive power procurement. In order to financially compensate a synchronous generator for its reactive power support, a payment function expectation of generator has been defined and formulated so that the Independent System Operator (ISO) can easily call for reactive bids from all players [12]. Consequently, according to the price offers of reactive power and technical constraints in reactive power planning, a two-step approach has been suggested to determine the optimal reactive power procurement plan for the ISO. A competitive reactive power market has been designed in Ref. [13]. The reactive power cost of a synchronous generator has been extracted from its capability curve, therefore, a four-component bidding structure has been proposed. In Ref. [14], a two-step reactive power market has been proposed. In the first step, reactive power is determined on a seasonal basis and in the second step it is dispatched for real time operation. A day ahead reactive power market based on a pay-as-bid clearing mechanism has been presented in Ref. [15]. In order to mitigate market power, a localized reactive power market has been proposed in Ref. [16].

However, in distribution systems, the reactive power market is a new topic and there are few studies about it [17–19]. On the other hand, due to the growth of DG penetration into distribution systems, development of a reactive market in distribution system consisting DGs is gaining more meaning. In Ref. [17], the framework of a reactive power market has been addressed. DG owners and micro-grids submit their reactive bids to the VAr market, which is settled based on an optimal power flow aiming at minimizing the cost of reactive power purchased by the distribution system operator (DSO). A few studies have explored the potential of Wind Turbines (WTs) to compensate reactive power by participating in a reactive power market (e.g., Ref. [18,19]).

The presence of uncertainty in the behavior of real power systems can invalidate the results of the mentioned researches. To consider the unpredictable features of renewable energy resources and the uncertainty of load demand and market price, using an efficient stochastic framework is inevitable [20]. A stochastic multi-objective optimal reactive power dispatch has been proposed under load and wind power uncertainties in Ref. [21]. In Ref. [22], a stochastic multi-objective scheduling method is proposed to dispatch energy and reserve in a smart distribution system with demand response (DR) programs considering the same uncertainties as Ref. [21]. Ref. [23] has presented a scenario-based stochastic programming model for sequential active and reactive

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