Energy Conversion and Management 106 (2015) 495–509

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Economic-environmental active and reactive power scheduling of modern distribution systems in presence of wind generations: A distribution market-based approach

Abouzar Samimi [a], Ahad Kazemi [a], Pierluigi Siano [b,*]

[a] Center of Excellence for Power Systems Automation and Operation, Iran University of Science and Technology, Tehran, Iran
[b] Department of Industrial Engineering, University of Salerno, Fisciano, SA 84084, Italy

ARTICLE INFO

Article history:
Received 24 July 2015
Accepted 26 September 2015

Keywords:
Distributed energy resource
Reactive power offer
Reactive power capability
Active and reactive power markets
CO_2 emission
Wind turbine

ABSTRACT

Distribution System Operator (DSO) is responsible for active and reactive power scheduling in a distribution system. DSO purchases its active and reactive power requirements from Distributed Energy Resources (DERs) as well as the wholesale electricity market. In this paper, a new economical/environmental operational scheduling method based on sequential day-ahead active and reactive power markets at distribution level is proposed to dispatch active and reactive powers in distribution systems with high penetration of DERs. In the proposed model, after day-ahead active power market was cleared the participants submit their reactive power bids and then the reactive power market will be settled. At distribution level, developing a Var market, in which DERs like synchronous machine-based Distributed Generation (DG) units and Wind Turbines (WTs) could offer their reactive power prices, DERs are motivated to actively participate in the Volt/VAr Control (VVC) problem. To achieve this purpose, based on the capability curves of considered DERs, innovative multi-component reactive power bidding structures for DERs are introduced. Moreover, the effect of reactive power market clearing on the active power scheduling is explicitly considered into the proposed model by rescheduling of active power by usage of energy-balance service bids. On the other hand, environmental concerns that arise from the operation of fossil fuel fired electric generators are included in the proposed model by employing CO_2 emission penalty cost. The suggested reactive power market is cleared through a mixed-integer nonlinear optimization program. The effectiveness of the proposed scheduling model is investigated through a typical 22-bus distribution test system over a 24-h period.

1. Introduction

1.1. State of the art and motivation

In recent years, environmental and economic considerations, as well as the need for more flexible electrical systems and rising global fuel prices are playing a key role in the development of distributed generation technologies, energy storage systems, demand response (DR) programs and advanced metering infrastructure that are now considered as essential components to meet the smart grid concept. Due to the high penetration of Distributed Generations (DGs), it seems reasonable to assume that some ancillary services could be provided by DGs in an economical and efficient way. At present, most of the installed DGs are commonly operated at unity power factor or fixed power factors in order to prevent interference with the conventional Volt/VAr Control (VVC) devices [1,2]. Since inverters coupled with DGs are able to support reactive power service as one of the most important ancillary services, reactive power could be efficiently provided by DGs. As a result, DGs could participate in the VVC problem.

Nowadays, all researches on VVC problem can be divided into two fundamentally different frameworks: *centralized offline control* and *real-time control*. In the first framework, scheduling of VVC devices has been obtained based on the forecasted load demand. In researches in this framework, various methodologies with different objective functions, such as total energy cost offered by generation units, electrical energy losses, voltage deviations and total emission of generation units, have been adopted to manage VVC problem [3–8]. By developing Supervisory Control and Data Acquisition (SCADA) capabilities and communication infrastructure,

---

* Corresponding author. Tel./fax: +39 089964294.
E-mail addresses: abouzarsamimi@iust.ac.ir (A. Samimi), kazemi@iust.ac.ir (A. Kazemi), psiano@unisa.it (P. Siano).

http://dx.doi.org/10.1016/j.enconman.2015.09.070
0196-8904/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

Acronyms

DSO	Distribution System Operator
DER	Distributed Energy Resource
DG	Distributed Generation
WT	Wind Turbine
QPF	reactive power (Q) payment function
EPF	Expected Payment Function
MCP	Market Clearing Price
LOC	Lost Opportunity Cost
OLTC	on-load tap changer

Parameters and variables

h	index of hours from 1 to Nh
NWT/NDG	total number of WTs/DGs
$NBus$	total number of buses
$V_{t,i}$	voltage at ith DG terminal bus
E_i^{max}	maximum internal voltage of DG ith
$X_{s,i}$	synchronous reactance of DG ith
$S_{DG,i}^{rated}$	nominal apparent power of DG ith
$P_{DG,i}^{h}/Q_{DG,i}^{h}$	scheduled active/reactive power of DG ith at hour h
$P_{DG,i}^{min}/P_{DG,i}^{max}$	minimum/maximum active power generation of DG ith
$Q_{DG,i}^{min}/Q_{DG,i}^{max}$	minimum/maximum reactive power generation of DG ith
$Q_{DG,i}^{mnd,h}$	maximum mandatory reactive power produced by DG ith at hour h
$\rho_{0,i}$	availability cost of DG ith
$\rho_{1,i}/\rho_{2,i}$	offered cost of losses of DG ith for operating in the under/over excitation mode
$\rho_{3,i}$	offered opportunity cost of DG ith
$W_{0,i}, W_{1,i}, W_{2,i}, W_{3,i}, W_{4,i}$	binary variables related to Q payment function of DG ith
V_c/I_c	converter voltage/current
$V_{c,max}/I_{c,max}$	converter's maximum voltage/current
a_l/b_l	constants of power module used for WT
V_g	voltage at the grid connection point of WT
$P_{WT,i}^{h}/Q_{WT,i}^{h}$	scheduled active/reactive power of WT ith at hour h
$P_{WT,i}^{min}$	minimum active power generation of WT ith
$P_{WT,i}^{Forecast,h}$	forecasted active power output of WT ith at hour h
$P_{WT}^{h,max}$	maximum forecasted active power of a WT at hour h
ΔP_{max}	maximum hourly variation of wind power from the forecasted value
$Q_{WT}^{h,cap}$	reactive power generation capability of a WT at hour h
$Q_{WT}^{h,av}$	maximum available reactive power of a WT at hour h
$Q_{WT,i}^{mnd,h}$	maximum mandatory reactive power produced by WT ith at hour h
$m_{0,i}$	offered availability price of WT ith
$m_{1,i}$	offered cost of losses of WT ith
$m_{2,i}$	offered opportunity cost of WT ith
$Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i}$	binary variables related to Q payment function of WT ith
$QPF_{DG,i}$	reactive power payment function of DG ith
$QPF_{WT,i}$	reactive power payment function of WT ith
$P_{grid}^{ini,h}/P_{DG,i}^{ini,h}/P_{WT,i}^{ini,h}$	initial scheduled active power purchased from the main grid/DG ith/WT ith at hour h
$\Delta P_{grid}^{L,h}$	change in the initial scheduled active power of the main grid corresponding to the contribution of the main grid to balance active losses at hour h
$\Delta P_{DG,i}^{L,h}/\Delta P_{WT,i}^{L,h}$	change in the initial scheduled active power corresponding to the contribution of DG ith/WT ith to balance active losses at hour h
$\Delta P_{DG,i}^{Q,h}$	amount of reduction in the active power of DG ith required to increase its reactive power at hour h
$\Delta P_{WT,i}^{Q,h}$	amount of the reduction with respect to the forecasted active power of WT ith to increase its reactive power at hour h
$P_{grid}^{Bal,h}$	active power balance service purchased from the main grid at hour h
$P_{DG,i}^{Bal,h}$	active power balance service purchased from DG ith at hour h
P_{grid}^{h}	scheduled active power of the main grid at hour h
$P_{grid}^{max,h}$	maximum capacity limit of the main grid
Q_{grid}^{h}	imported reactive power from the main grid at hour h
$\pi_{DG,i}^{h}/\pi_{WT,i}^{h}$	price of the electrical energy offered by the DG ith and WT ith at hour h
π_{grid}^{h}	wholesale market energy price at hour h
$\rho_{Q,grid}^{h}$	reactive power price of wholesale market at hour h
$\rho_{grid}^{Bal,h}$	energy-balance service price of the main grid at hour h
$\rho_{DG,i}^{Bal,h}$	energy-balance service price of DG ith at hour h
$x_{DG,i}/x_{WT,i}$	cap on reduction in active power of DG ith/WT ith
$COST_{grid}^{Emission}$	penalty cost function of the CO_2 emission related to the main grid
$COST_{DG,i}^{Emission}$	penalty cost function of the CO_2 emission of DG ith
$CO_{2,grid}$	average CO_2 emission from the bulk electric system per unit of the generated energy
$CO_{2,DG,i}$	CO_2 emission from the DG ith
$CO_{2,cap}$	allowable CO_2 emission
EPC_{CO_2}	CO_2 emission penalty cost
pf_{mnd}	mandatory power factor
MCP_h	market clearing price at hour h
Tap_i^h	tap position of transformer ith at hour h
Tap_i^{min}/Tap_i^{max}	minimum/maximum tap position of transformer ith
$CStep_i^h$	step position of switched capacitor ith at hour h
$CStep_i^{min}/CStep_i^{max}$	minimum/maximum step of switched capacitor ith at hour h
$P_{D,i}^{h}$	active power demand at bus i at hour h
V_i^h	voltage of bus i at hour h
V_{max}/V_{min}	maximum/minimum voltage magnitude

Remote Terminal Units (RTUs) as measurement and control systems are widely used throughout the modern distribution systems. On the basis of these capabilities, the real-time control methods are implemented to control the VVC equipment based on real-time and local measurements [9–13].

Although, many researches on energy and reserve scheduling have been performed in smart distribution systems with renewable generations and electric vehicles [2,14–19], however, few studies about joint active and reactive power scheduling in distribution systems with high penetration of Distributed Energy Resources (DERs) have been reported. Besides, in few researches, the possibility of expansion a reactive power market in distribution systems in presence of DERs has been explored. Therefore, by ever-increasing integration of DERs into the grid, development a reactive power market in distribution systems with the participation of DERs is gaining more importance.