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



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#### 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 energybalance 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<sub>2</sub> 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.

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#### 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,

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Nomenclature

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$\begin{array}{lll} P_{WT,i}^{h} Q_{WT,i}^{h} & \text{scheduled active/reactive power of WT ith at hour h} \\ P_{WT,i}^{min} & \text{minimum active power generation of WT ith} \\ P_{WT,i}^{min} & \text{minimum active power output of WT ith at hour h} \\ P_{WT,i}^{h,max} & \text{forecasted active power output of WT ith at hour h} \\ P_{WT,i}^{h,max} & \text{maximum forecasted active power of a WT at hour h} \\ \Delta P_{max} & \text{maximum hourly variation of wind power from the} \\ forecasted value & \\ Q_{WT}^{h,av} & \text{reactive power generation capability of a WT at hour h} \\ Q_{WT,i}^{h,av} & \text{maximum mandatory reactive power of a WT at hour h} \\ Q_{WT,i}^{h,av} & \text{maximum mandatory reactive power of a WT at hour h} \\ Q_{WT,i}^{mnd,h} & \text{maximum mandatory reactive power produced by WT} \\ ith at hour h & \\ M_{0,i} & \text{offered availability price of WT ith} \\ m_{1,i} & \text{offered opportunity cost of WT ith} \\ m_{2,i} & \text{offered opportunity cost of WT ith} \\ m_{2,i} & \text{offered opportunity cost of WT ith} \\ Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i} & \text{binary variables related to Q payment function of} \end{array}$				2,8,14	
$P_{WT,i}^{min}$ minimum active power generation of WT ith $EPC_{CO_2}$ $CO_2$ emission $P_{WT,i}^{inorecast.h}$ forecasted active power output of WT ith at hour h $EPC_{CO_2}$ $CO_2$ emission $P_{WT,i}^{himax}$ maximum forecasted active power of a WT at hour hmaximum hourly variation of wind power from the forecasted value $P_{max}^{himax}$ mandatory power factor $Q_{WT}^{himax}$ maximum available reactive power generation capability of a WT at hour h $MCP_h$ market clearing price at hour h $Q_{WT}^{hinax}$ maximum available reactive power of a WT at hour h $Tap_i^{hin}/Tap_i^{max}$ minimum/maximum tap position of transformer $Q_{WT}^{hinax}$ maximum mandatory reactive power of a WT at hour h $CStep_i^{min}/CStep_i^{max}$ minimum/maximum step of switched capacitor $Q_{WT,i}^{mna,i}$ offered cost of losses of WT ith $P_{D,i}^{hinax}$ scitive power demand at bus i at hour h $V_i^{min}$ $V_{max}/V_{min}$ $V_{max}/V_{min}$ $Maximum/minimum voltage magnitude$				$CO_{2,DG,i}$	$CO_2$ emission from the DG <i>i</i> th
$\begin{array}{llllllllllllllllllllllllllllllllllll$	l			CO <sub>2,cap</sub>	
$\begin{array}{llllllllllllllllllllllllllllllllllll$	l				
$ \begin{array}{llllllllllllllllllllllllllllllllllll$	l	<sup>1</sup> WT.i			
$ \begin{array}{llllllllllllllllllllllllllllllllllll$		$P_{WT}^{h,max}$			
$Q_{WT}^{h,cap}$ $Q_{WT}^{h,cap}$ reactive power generation capability of a WT at hour h maximum available reactive power of a WT at hour h maximum mandatory reactive power of a WT at hour h maximum mandatory reactive power produced by WT ith at hour hith Step position of switched capacitor ith at hour h $CStep_i^{max}$ minimum/maximum step of switched capaci- tor ith at hour h $M_{0,i}$ $m_{1,i}$ $m_{2,i}$ offered opportunity cost of WT ith $Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i}$ ith $V_{max}/V_{min}$ $M_{0,i}$ $M_{0,i}$ $M_{0,i}$ $M_{0,i}$	l	$\Delta P_{max}$			
$Q_{WT}^{h,av}$ $W_{WT,i}^{ma,h}$ $maximum mandatory reactive power of a WT at hour hmaximum mandatory reactive power produced by WTith at hour hCStep_i^nminimum/maximum step of switched capaci-tor ith at hour hCStep_i^{max}minimum/maximum step of switched capaci-tor ith at hour hP_{D,i}^hactive power demand at bus i at hour hV_i^hvoltage of bus i at hour hV_{max}^h/V_{min}maximum voltage magnitude$		oh can		Tap <sub>i</sub> <sup>man</sup> /Taj	
$Q_{WT,i}^{mal,h}$ maximum mandatory reactive power of a W1 at nour n $Q_{WT,i}^{mal,h}$ 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		Q <sub>WT</sub>		CStanh	
$V_{WT,i}^{h}$ maximum mandatory reactive power produced by W1 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	l	$Q_{WT}^{n,uv}$	-	CStep <sup>min</sup> /	Step position of switched capacitor in at nour fi
$m_{0,i}$ offered availability price of WT ith $m_{1,i}$ $P_{D,i}$ offered cost of losses of WT ith $m_{2,i}$ active power demand at bus 1 at hour h $V_i^h$ $V_{iax}/V_{min}$ $m_{2,i}$ 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 $P_{D,i}$ $V_i^h$ $V_{max}/V_{min}$ active power demand at bus 1 at hour h $V_{iax}$	l	$Q_{WT,i}^{mnd,h}$			tor <i>i</i> th at hour h
$m_{1,i}$ offered opportunity cost of WT <i>i</i> th $V_{max}/V_{min}$ maximum/minimum voltage magnitude $Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i}$ binary variables related to Q payment function of	l	m <sub>o i</sub>		$P_{D,i}^n$	
$m_{2,i}$ offered opportunity cost of WT <i>i</i> th $Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i}$ binary variables related to Q payment function of				$V_i^{\prime\prime}$	
$Z_{0,i}, Z_{1,i}, Z_{2,i}, Z_{3,i}$ binary variables related to Q payment function of	l	$m_{2,i}$	offered opportunity cost of WT <i>i</i> th	v <sub>max</sub> /V <sub>min</sub>	maximum/minimum voltage magnitude
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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 everincreasing integration of DERs into the grid, development a reactive power market in distribution systems with the participation of DERs is gaining more importance. Download English Version:

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