Energy Conversion and Management 88 (2014) 985-998







Energy Conversion and Management

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

A stochastic framework for the grid integration of wind power using flexible load approach



E. Heydarian-Forushani^a, M.P. Moghaddam^b, M.K. Sheikh-El-Eslami^b, M. Shafie-khah^c, J.P.S. Catalão^{c,d,e,*}

^a Iran University of Science and Technology, 16846-13114 Tehran, Iran

^b Tarbiat Modares University, 14115-111 Tehran, Iran

^c University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal

^d INESC-ID, R. Alves Redol, 9, 1000-029 Lisbon, Portugal

^e IST, University of Lisbon, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal

ARTICLE INFO

Article history: Received 7 June 2014 Accepted 16 September 2014 Available online 3 October 2014

Keywords: Wind power integration Demand response programs Flexible load Stochastic programming

ABSTRACT

Wind power integration has always been a key research area due to the green future power system target. However, the intermittent nature of wind power may impose some technical and economic challenges to Independent System Operators (ISOs) and increase the need for additional flexibility. Motivated by this need, this paper focuses on the potential of Demand Response Programs (DRPs) as an option to contribute to the flexible operation of power systems. On this basis, in order to consider the uncertain nature of wind power and the reality of electricity market, a Stochastic Network Constrained Unit Commitment associated with DR (SNCUCDR) is presented to schedule both generation units and responsive loads in power systems with high penetration of wind power. Afterwards, the effects of both price-based and incentive-based DRPs are evaluated, as well as DR participation levels and electricity tariffs on providing a flexible load profile and facilitating grid integration of wind power. For this reason, novel quantitative indices for evaluating flexibility are defined to assess the success of DRPs in terms of wind integration. Sensitivity studies indicate that DR types and customer participation levels are the main factors to modify the system load profile to support wind power integration.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The predominant share of conventional fossil fuel units in the electricity supply mix has increased concerns on climate change, energy security and price volatility. To address these concerns, many power systems have started changing their energy generation portfolios to include significant amounts of renewable energy resources [1]. Although most renewable energy resources have a dramatic installed capacity growth in the recent years, the development of wind power has enhanced much more, especially. The global installed wind generation capacity increased from 10 megawatts (MW) in 1980 to 282 gigawatts (GW) by the end of 2012 [2].

However, uncertain and non-dispatchable characteristics of wind power compared to other conventional plants may pose important challenges to power system operation. Highly intermittent nature of wind power may impair power system's balance between supply and demand and lead to system reliability endan-

* Corresponding author at: University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal. Tel.: +351 275 329914; fax: +351 275 329972.

E-mail address: catalao@ubi.pt (J.P.S. Catalão).

http://dx.doi.org/10.1016/j.enconman.2014.09.048 0196-8904/© 2014 Elsevier Ltd. All rights reserved. germent as well as higher operation costs. Furthermore, ramping requirement of the system in the presence of wind generation is more than the case where no wind power is generated. In such situation, existing generation units must ramp up and down more frequently and operate in de-rated capacity. As a result, the average operating efficiency will be decreased [3].

On this basis, a challenge that system operators are facing with large-scale integration of wind power is how to cope with and mitigate the wind variability and forecast uncertainties. To address the mentioned challenges, several different studies have conducted on large-scale grid integration of wind power. In this regard, providing a more flexible power grid is a common aim that can be seen in all previous researches. To achieve that aim, several solutions are presented for power system operators in former publications which can be classified into three major categories:

- (1) Utilizing energy storage technologies.
- (2) Providing additional reserve capacity throughout electricity market and improving market mechanism, rules and structures.
- (3) Using flexible demand side resources.

Nomenclature

$ b \text{index of system buses} \\ i \text{index of generating unit} \\ i \text{index of transmission line} \\ m \text{segment index for linearized fuel cost} \\ n \text{segment index for linearized total incentive curve} \\ s \text{index of scenarios} \\ i \text{t.t'} \text{index of scenarios} \\ r_{tt} reactance of line \\ r_{tt} \text{index of segments for the piecewise linearized total incentive curve} \\ NSE_i, NSF_i \text{number of segments for the piecewise linearized total incentive curve} \\ NS \text{number of segments for the piecewise linearized total incentive curve} \\ Parameters \\ AS_n(t) \text{slope of segment n in linearized total incentive curve of unit i} \\ (S/MW h) \\ d_0(t) \text{initial electricity demand (MW)} \\ C_i^{RR} \text{offered capacity cost of spinning reserve provision of} \\ unit i \ \text{in hour } t (S/MW) \\ C_i^{RR} \text{offered capacity cost of non-spinning reserve provision of} \\ unit i \ \text{in hour } t (S/MW h) \\ e_(m) \text{slope of segment m in linearized emission curve of unit i i hour t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized measure provision of} \\ unit i \ \text{in hour } t (S/MW) \\ C_i^{RR} \text{offered capacity cost of non-spinning reserve provision of} \\ unit i \ \text{in hour } t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized emission curve of unit i i nour t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized emission curve of unit i i nour t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized mission curve of unit i i nour t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized measure provision of} \\ unit i \ \text{in hour } t (S/MW h) \\ e_i(m) \text{slope of segment m in linearized mission curve of unit i i (S/h) \\ e_i(m) \text{slope of segment m in linearized mission curve of unit i i (S/h) \\ e_i(m) \text{slope of segment m in linearized mission curve of unit i i hour t (S/MW h) \\ e_i(m) \text{offered energy cost of non-spinning reserve provision of} \\ uni$	1	Indices		SU _i /SD _i	start-up/shutdov
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	l	Ь	index of system buses	UT_i/DT_i	minimum up/do
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	i	i	index of generating unit	W_{st}^{max}	available wind p
$\begin{array}{llllllllllllllllllllllllllllllllllll$	l	l	index of transmission line	X _l	reactance of line
nsegment index for linearized total incentive curve s π_{FT} FIT incentive val π_{cur} sindex of scenarios π_{cur} π_{cur} cost of wind poo $\rho_0(t)$ NSE _i , NSF _i number of segments for the piecewise linearized emission and fuel cost curves of unit i π_{cur} cost of wind poo $\rho_0(t)$ NSnumber of segments for the piecewise linearized incentive curve π_{cur} cost of wind poo $\rho_0(t)$ Parametersnumber of segment n in linearized total incentive curve in hour t (MW h) $Variables$ C ^e (m)slope of segment n in linearized fuel cost curve of unit i (\$/MW h) WW $d_0(t)$ initial electricity demand (MW) P_{tis}^{int} C ^{sin} offered capacity cost of spinning reserve provision of unit i in hour t (\$/MW) P_{bt}^{int} C ^{sin} offered capacity cost of non-spinning reserve provision of unit i in hour t (\$/MW h) NS_{tit} C ^{rie} offered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) NS_{tit} Criftoffered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) NS_{tit} Criftoffered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) Ns_{tit} ectr $(MW h)$ Ns_{tit} (m) </td <td>1</td> <td>т</td> <td>segment index for linearized fuel cost</td> <td>η_d</td> <td>customer partici</td>	1	т	segment index for linearized fuel cost	η_d	customer partici
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1	n	segment index for linearized total incentive curve	π_{FIT}	FIT incentive val
t, t' index of hours $\rho_0(t)$ initial electricity NSE_i, NSF_i number of segments for the piecewise linearized ω_s probability of with NS number of segments for the piecewise linearized total incentive curve $Variables$ NS number of segment n in linearized total incentive curve in hour t (MW h) $Variables$ $Parameters$ $AS_n(t)$ slope of segment n in linearized total incentive curve of hour t (MW h) $Variables$ $C_i^e(m)$ slope of segment m in linearized fuel cost curve of unit i ($\$/MW$ h) $Variables$ $Variables$ $d_0(t)$ initial electricity demand (MW) P_{its}^{ord} modified deman DR (MW) C_i^{sre} offered capacity cost of spinning reserve provision of unit i in hour t ($\$/MW$) SR_{it} scheduled non-sp C_{it}^{re} offered energy cost of non-spinning reserve provision of unit i in hour t ($\$/MW$ h) SR_{it} scheduled non-sp C_{it}^{re} offered energy cost of non-spinning reserve provision of unit i in hour t ($\$/MW$ h) NSR_{it} scheduled non-sp $e_{it}(m)$ slope of segment m in linearized emission curve of unit i ($R_{it}(m)$ $maio s$ (MW h) NKW h) $e_{it}(m)$ slope of segment m in linearized emission curve of unit i ($R_{it}(m)$ $maio s$ (MW h) $e_{it}(m)$ slope of segment m in linearized emission curve of unit i ($R_{it}(m)$ $maio s$ (MW h) $e_{it}(m)$ slope of segment m in linearized emission curve of unit i ($R_{it}(m)$ $maio s$ (MW h) $e_{it}(m)$ slope o	5	S	index of scenarios	π_{cur}	cost of wind pov
$\begin{array}{llllllllllllllllllllllllllllllllllll$	1	t. t'	index of hours	$\rho_0(t)$	initial electricity
I_{int} emission and fuel cost curves of unit i V_{int} NSnumber of segments for the piecewise linearized total incentive curve $Variables$ $Parameters$ $S_n(t)$ slope of segment n in linearized total incentive curve in hour t (MW h) $Variables$ $C_i^e(m)$ slope of segment m in linearized fuel cost curve of unit i ($\$/MW$ h) $Variables$ $d_0(t)$ initial electricity demand (MW) $P_{its}^{er}(m)$ generation of segment m in linearized fuel cost curve of unit i ($\$/MW$ h) $P_{its}^{ord}(m)$ $P_{its}^{ord}(m)$ $d_0(t)$ initial electricity demand (MW) $P_{its}^{ord}(m)$ ($\$/MW$) $P_{its}^{ord}(m)$ C_{it}^{er} $Offered$ capacity cost of spinning reserve provision of unit i in hour t ($\$/MW$) SR_{it} scheduled spinni SR_{it} C_{it}^{re} offered energy cost of spinning reserve provision of unit i in hour t ($\$/MW$ h) NSR_{it} $S(MW h)C_{it}^{re}offered energy cost of spinning reserve provision ofunit i in hour t (\$/MW h)SR_{it}S(MW h)C_{it}^{re}offered energy cost of non-spinning reserve provision ofunit i in hour t (\$/MW h)NSR_{it}S(MW h)C_{it}^{re}offered energy cost of non-spinning reserve provision ofunit i in hour t (\$/MW h)NSR_{it}S(MW h)E(C)environmental cost coefficient of pollutants (\$/kg)E_{it}v_n(t)award of segmentM^{int}integrated windS_{its}L^{re}_{it}lower limit on the fuel cost of unit i (\$/h)E_{it}V_{it}E_{it}E(K, I')$	1	NSE, NSF	number of segments for the piecewise linearized	ω_{s}	probability of wi
NSnumber of segments for the piecewise linearized total incentive curveVariablesNSnumber of segments for the piecewise linearized total incentive curveVariablesParameters $AS_n(t)$ slope of segment n in linearized total incentive curve in hour t (MW h) $Variables$ $AS_n(t)$ slope of segment m in linearized fuel cost curve of unit i (\$/MW h) $Variables$ $d_0(t)$ initial electricity demand (MW) P_{tis}^{er} (MW h) C_{tit}^{er} offered capacity cost of spinning reserve provision of unit i in hour t (\$/MW) P_{tot}^{ord} C_{tit}^{re} offered capacity cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled spinni SR_{it} scheduled non-s SR_{it} C_{tit}^{re} offered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s SR_{it} C_{tit}^{re} offered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s SR_{it} C_{tit}^{me} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s SR_{it} C_{tit}^{me} offered energy cost of onon-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s SR_{it} C_{it}^{me} offered energy cost of of unit i (S/hW h) SR_{it} scheduled non-s SR_{it} C_{it}^{me} offered energy cost of on-spinning reserve provision of unit i in hour t (\$/MW h) C_{it}^{me} offered energy cost of ord SR_{it} C_{it}^{me} offered energy cost of ord SR_{it} C_{it}^{me} offered ener		0	emission and fuel cost curves of unit <i>i</i>	5	1 5
incentive curve incentive curve in a finite sector of the	1	NS	number of segments for the piecewise linearized total	Variables	
Parameters F_{its} power flow three $AS_n(t)$ slope of segment n in linearized total incentive curve in hour t (MW h) F_{its} power flow three $C_i^e(m)$ slope of segment m in linearized fuel cost curve of unit i (\$/MW h) $P_{its}^e(m)$ generation of sec modified deman DR (MW) $d_0(t)$ initial electricity demand (MW) $P_{its}^{ec}(m)$ generation of sec modified deman DR (MW) C_{it}^{re} offered capacity cost of spinning reserve provision of unit i in hour t (\$/MW) P_{its}^{oto} modified deman DR (MW) C_{it}^{re} offered capacity cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s s SR_{it} scheduled non-s s SR_{it} C_{it}^{re} offered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s s SR_{it} scheduled non-s s SR_{it} C_{it}^{re} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s s SR_{it} scheduled non-s s SR_{it} C_{it}^{re} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} scheduled non-s s SR_{it} SR_{it} C_{it}^{re} offered energy cost of of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h) C_{it}^{re} lower limit on the emission cost of unit i (\$/h) $v_n(t)$ award of segment hour t (\$/MW h) ECC environmental cost coefficient of pollutants (\$/kg) $v_n(t)$			incentive curve	$C_{\text{rppp}}(t)$	cost of customer
Parameters I_{its} bower how three the time $AS_n(t)$ slope of segment n in linearized total incentive curve in hour t (MW h) V_{it}/Z_{it} binary status ind to any status ind Y_{it}/Z_{it} $C_i^e(m)$ slope of segment m in linearized fuel cost curve of unit i (\$/MW h) $P_{its}^{er}(m)$ generation of se (MW h) $d_0(t)$ initial electricity demand (MW) $P_{bt}^{er}(m)$ modified deman DR (MW) C_{it}^{SR} offered capacity cost of spinning reserve provision of unit i in hour t (\$/MW) DR (MW) C_{it}^{SR} offered capacity cost of non-spinning reserve provision of unit i in hour t (\$/MW) NSR_{it} C_{it}^{re} offered energy cost of spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} C_{it}^{re} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} C_{it}^{nre} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} C_{it}^{mre} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) SR_{it} $e_i(m)$ slope of segment m in linearized emission curve of unit i (Kg/MW h) $q_{its}(m)$ ECC environmental cost coefficient of pollutants (\$/kg) $v_n(t)$ E_{it} lower limit on the emission cost of unit i (\$/h) W_{oth}^{er} st E_{it} lower limit on the fuel cost of unit i (\$/h) W_{oth}^{er} st E_{it} lower limit on the fuel cost of unit i (\$/h) W_{oth}^{er} st </td <td></td> <td></td> <td></td> <td>$C_{EDRP}(t)$</td> <td>nower flow throw</td>				$C_{EDRP}(t)$	nower flow throw
$\begin{array}{llllllllllllllllllllllllllllllllllll$	1	Paramoto	rs	I IIS	hinary status ind
$\begin{array}{c} \text{MS}_{n}(t) & \text{solpe of segment } n in interared total interface total integrate dimension of unit i in integrate total integrate dimension of unit i integrate total integrate dimension into i i ($/MW h) integrate dimension into i i ($/h) integrate dimension into i i ($/h] integrate dimins integrated into bits b (MW) integr$	1	$\Delta S(t)$	slope of segment n in linearized total incentive curve in	N: 17.	binary start-un/s
$\begin{array}{c} C_{i}^{e}(m) & \text{slope of segment } m \text{ in linearized fuel cost curve of unit } i \\ (\$/MW h) & (\$/WW h) \\ d_{0}(t) & \text{initial electricity demand (MW)} & p_{bt}^{\text{mod}} & MW h \\ C_{it}^{SR} & \text{offered capacity cost of spinning reserve provision of unit } i \text{ in hour } t (\$/MW) & (MW) \\ C_{it}^{NSR} & \text{offered capacity cost of non-spinning reserve provision of unit } i \text{ in hour } t (\$/MW) & NSR_{it} & \text{scheduled spinn} \\ fire & \text{offered energy cost of spinning reserve provision of unit } i \text{ in hour } t (\$/MW h) & NSR_{it} & \text{scheduled non-s} \\ C_{it}^{re} & \text{offered energy cost of spinning reserve provision of unit } i \text{ in hour } t (\$/MW h) & NSR_{it} & \text{scheduled non-s} \\ C_{it}^{rre} & \text{offered energy cost of non-spinning reserve provision of unit } i \text{ in hour } t (\$/MW h) & nario s (MW h) \\ C_{it}^{nre} & \text{offered energy cost of non-spinning reserve provision of unit } s (MW h) \\ e_{i}(m) & \text{slope of segment } m \text{ in linearized emission curve of unit } i \\ (MW h) & \text{award of segment } m \text{ in linearized emission curve of unit } i \\ (MW h) & \text{wh} h \\ ECC & environmental cost coefficient of pollutants (\$/kg) & v_n(t) & \text{award of segment } hour t (\$/MW h) \\ Em_i & \text{lower limit on the emission cost of unit } i (\$/h) & \text{wint } \\ f_i & \text{lower limit on the fuel cost of unit } i (\$/h) & \text{wint } \\ f_i & \text{lower limit on the fuel cost of unit } (\$/h) & \text{wint } \\ P_{in}^{max} & \text{minimum/maximum output limit (MW)} \\ RU_i/RD_i & \text{ramp up/down (MW/h) \end{array}$	1	$D_n(t)$	sope of segment <i>n</i> in incanzed total incentive curve in bour t (MW b)	$P_{i}^{e}(m)$	generation of se
$\begin{array}{c} C_{i}(m) & \text{slope of segment } m \text{ in measured rule (cost curve of unit } r \\ (\$/MW h) & P_{bt}^{\text{mod}} & \text{modified deman} \\ d_{0}(t) & \text{initial electricity demand (MW)} & P_{bt}^{\text{mod}} & DR (MW) \\ C_{it}^{SR} & \text{offered capacity cost of spinning reserve provision of unit } i & \text{in hour } t (\$/MW) & SR_{it} & \text{scheduled spinn} \\ of unit i & \text{in hour } t (\$/MW) & SR_{it} & \text{scheduled spinn} \\ fire & \text{offered energy cost of spinning reserve provision of unit } i & \text{in hour } t (\$/MW h) & SR_{it} & \text{scheduled spinn} \\ C_{it}^{rre} & \text{offered energy cost of non-spinning reserve provision of unit } i & \text{in hour } t (\$/MW h) & SR_{it} & \text{scheduled non-spinning reserve provision of unit } s (MW h) \\ C_{it}^{rre} & \text{offered energy cost of non-spinning reserve provision of unit } s (MW h) & Slope of segment m in linearized emission curve of unit i & s(MW h) \\ e_{i}(m) & \text{slope of segment } m & \text{in linearized emission curve of unit } i & q_{its}(m) & generation of se & (MW h) \\ ECC & environmental cost coefficient of pollutants (\$/kg) & v_{n}(t) & award of segment & hour t (\$/MW h) \\ \underline{ECC} & \text{environmental cost coefficient of pultants (\$/h) & maxind of segment & hour t (\$/MW h) \\ \underline{ECC} & \text{environmental cost coefficient of pultants (\$/h) & maxind of segment & hour t (\$/MW h) \\ \underline{ECC} & \text{environmental cost coefficient of pultants (\$/h) & maxind of segment & hour t (\$/MW h) \\ \underline{ECC} & \text{environmental cost coefficient of pultants (\$/h) & maxind of segment & hour t (\$/MW h) \\ \underline{ET}_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) & m_{st} & \text{integrated wind } \\ \underline{E}_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) & M_{st} & \text{integrated wind } \\ \underline{E}_{i} & \text{lower limit on the fuel cost of unit } (MW) \\ RU_{i}/RD_{i} & \text{ramp up/down (MW/h) \\ \end{array} \right)$		$C^{e}(m)$	slope of segment m in linearized fuel cost curve of unit i	its (m)	(MW h)
$\begin{array}{c} (s)_{i}(WW H) \\ d_{0}(t) & \text{initial electricity demand (MW)} \\ C_{it}^{SR} & \text{offered capacity cost of spinning reserve provision of } \\ wit i \text{ in hour } t (\$/MW) \\ C_{it}^{NSR} & \text{offered capacity cost of non-spinning reserve provision of } \\ wit i \text{ in hour } t (\$/MW) \\ C_{it}^{NSR} & \text{offered capacity cost of non-spinning reserve provision of unit } \\ i \text{ in hour } t (\$/MW) \\ C_{it}^{re} & \text{offered energy cost of spinning reserve provision of unit } \\ i \text{ in hour } t (\$/MW h) \\ C_{it}^{rre} & \text{offered energy cost of non-spinning reserve provision of unit } \\ i \text{ in hour } t (\$/MW h) \\ c_{it}^{rre} & \text{offered energy cost of non-spinning reserve provision of unit } \\ e_{i}(m) & \text{slope of segment } m \text{ in linearized emission curve of unit } \\ e_{i}(m) & \text{slope of segment } m \text{ in linearized emission curve of unit } \\ E(t, t') & \text{elasticity of demand} \\ E_{i} & \text{lower limit on the emission cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ E_{i} & \text{lower limit on the fuel cost of unit } i (\$/h) \\ RU_{i}/RD_{i} & \text{ramp up/down (MW/h)} \end{array}$		$z_i(m)$	$(\xi/MM/b)$	pmod	modified deman
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		d(t)	(\$/19199 II) initial electricity demand (MW)	¹ bt	DR (MM/)
C_{it} bitefed capacity cost of spinning reserve provision of unit <i>i</i> in hour <i>t</i> (\$/MW) T_{its} colar scheduled spinn (MW) C_{it}^{NSR} offered capacity cost of non-spinning reserve provision of unit <i>i</i> in hour <i>t</i> (\$/MW) SR_{it} scheduled spinn 		C^{SR}	offered capacity cost of spinning records provision of	D tot	total scheduled
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		~it	unit i in hour t (\$/MW)	¹ its	
C_{it} of lefted capacity cost of non-spinning reserve provision NSR_{it} scheduled spinning C_{it}^{re} offered energy cost of spinning reserve provision of unit NSR_{it} scheduled non-si C_{it}^{re} offered energy cost of spinning reserve provision of unit sr_{its} deployed spinning i in hour t (\$/MW h) $s(MW h)$ $s(MW h)$ $s(MW h)$ C_{it}^{nre} offered energy cost of non-spinning reserve provision of nsr_{its} deployed non-spination of energy cost of non-spinning reserve provision of $e_i(m)$ slope of segment m in linearized emission curve of unit i $q_{its}(m)$ generation of se $kg/MW h$ $kg/MW h$ $marriso s (MW h)$ $marriso s (MW h)$ ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment $E(t, t')$ elasticity of demand $hour t ($/MW h)$ $marriso s (MW h)$ Em_i lower limit on the fuel cost of unit $i ($/h)$ W_{st}^{int} integrated wind V_{st}^{int} LD_b demand contribution of bus $b (MW)$ δ_{bts} voltage angle at P_i^{min}/P_i^{max} minimum/maximum output limit (MW) RU_i/RD_i ramp up/down (MW/h)		CNSR	offered capacity cost of non-spinning reserve provision	SR.	scheduled spinni
$\begin{array}{cccc} re \\ C_{it}^{re} & offered energy cost of spinning reserve provision of unit \\ i in hour t ($/MW h) \\ C_{it}^{nre} & offered energy cost of non-spinning reserve provision of \\ unit i in hour t ($/MW h) \\ e_i(m) & slope of segment m in linearized emission curve of unit i \\ (kg/MW h) \\ ECC & environmental cost coefficient of pollutants ($/kg) \\ E(t, t') & elasticity of demand \\ E_i & lower limit on the emission cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h) \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lower limit on the fuel cost of unit i ($/h] \\ E_i & lowe$		~it	of unit i in hour $t (f/MW)$	NSR.	scheduled pon-si
C_{it} onered energy cost of spinning reserve provision of unit S_{its} deployed spinning i in hour t (\$/MW h) s (MW h) s (MW h) C_{it}^{nre} offered energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h) nsr_{its} deployed non-sp nario s (MW h) $e_i(m)$ slope of segment m in linearized emission curve of unit i (kg/MW h) $q_{its}(m)$ generation of se (MW h)ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h)ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h)Emilower limit on the emission cost of unit i (\$/h) W_{st}^{int} integrated wind E_{it} integrated wind δ_{bts} ID_b demand contribution of bus b (MW) δ_{bts} voltage angle at P_i^{min}/P_i^{max} minimum/maximum output limit (MW) RU_i/RD_i ramp up/down (MW/h) MW/h	,	cre	of unit t in nour t ($\frac{1}{2}/\frac{1}{1000}$)	cr.	deployed spinnir
$\begin{array}{llllllllllllllllllllllllllllllllllll$		- it	in hour $t (\text{S}/\text{MW})$	SI its	c (MW b)
C_{it} bitefed energy cost of non-spinning reserve provision of unit i in hour t (\$/MW h)nario s (MW h) $e_i(m)$ slope of segment m in linearized emission curve of unit i (kg/MW h) $q_{its}(m)$ generation of se (MW h)ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h)ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h)ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h)Emilower limit on the emission cost of unit i (\$/h) W_{st}^{int} stcurtailed wind p voltage angle at P_i^{min}/P_i^{max} minimum/maximum output limit (MW) δ_{bts} RU _i /RD _i ramp up/down (MW/h)ramp up/down (MW/h) M_{st}^{int} M_{st}^{int}	,	cnre	t III IIOUI t (5/NIW II)	ncr.	deployed pop sp
$\begin{array}{c} \text{finit } r \text{ in Hour } r(\$/MW \text{ if}) \\ e_i(m) & \text{slope of segment } m \text{ in linearized emission curve of unit } i \\ (kg/MW \text{ h}) \\ ECC & \text{environmental cost coefficient of pollutants } (\$/kg) \\ E(t, t') & \text{elasticity of demand} \\ E_i & \text{lower limit on the emission cost of unit } i (\$/h) \\ E_i & \text{lower limit on the fuel cost of unit } i (\$/h) \\ D_b & \text{demand contribution of bus } b (MW) \\ RU_i/RD_i & \text{ramp up/down } (MW/h) \end{array}$		- it	unit i in hour $t (f) M(h)$	nsi _{its}	nario s (MW b)
$\begin{array}{llllllllllllllllllllllllllllllllllll$		$\alpha(m)$	ullit <i>i</i> iii flour <i>i</i> $(3/10100 \text{ II})$	a (m)	ranoration of co
ECCenvironmental cost coefficient of pollutants (\$/kg) $v_n(t)$ award of segment hour t (\$/MW h) $E(t, t')$ elasticity of demandhour t (\$/MW h) $E(t, t')$ elasticity of demandhour t (\$/MW h) Em_i lower limit on the emission cost of unit i (\$/h) W_{st}^{int} integrated wind E_i lower limit on the fuel cost of unit i (\$/h) W_{st}^{int} curtailed wind p LD_b demand contribution of bus b (MW) δ_{bts} voltage angle at P_i^{min}/P_i^{max} minimum/maximum output limit (MW) RU_i/RD_i ramp up/down (MW/h)	6	$z_i(m)$	Slope of segment <i>III</i> in intealized emission curve of unit i	$q_{its}(m)$	(MW b)
ECCEnvironmental cost coefficient of pointaints $(5/kg)$ $v_n(t)$ award of segment hour t $($/MW h)$ $E(t, t')$ elasticity of demandhour t $($/MW h)$ Em_i lower limit on the emission cost of unit i $($/h)$ W_{st}^{int} integrated wind E_i lower limit on the fuel cost of unit i $($/h)$ W_{st}^{int} curtailed wind p LD_b demand contribution of bus b (MW) δ_{bts} voltage angle at P_i^{min}/P_i^{max} minimum/maximum output limit (MW) RU_i/RD_i ramp up/down (MW/h)	1	FCC	(Kg/WW II)	a(t)	(IVIVV II)
$ \begin{array}{c} E(i,t') & \text{elasticity of definitid} & \text{four } t'(s/MW II) \\ \underline{Em}_i & \text{lower limit on the emission cost of unit } i(\$/h) & W_{st}^{\text{int}} & \text{integrated wind} \\ \underline{F_i} & \text{lower limit on the fuel cost of unit } i(\$/h) & W_{st}^{\text{int}} & \text{curtailed wind p} \\ \underline{LD}_b & \text{demand contribution of bus } b(MW) & \delta_{bts} & \text{voltage angle at} \\ P_i^{\min}/P_i^{\max} & \min(MW/h) & W_{st}^{\text{int}} & \text{curtailed wind p} \\ \underline{RU}_i/RD_i & \text{ramp up/down (MW/h)} \end{array} $	1		environmental cost coefficient of pollutants (\$/kg)	$v_n(t)$	hour t (C/MM/h)
$\frac{Em}{E_i} \text{lower limit on the emission cost of unit } i (\$/h) \qquad \qquad W_{st} \text{integrated whild} \\ \frac{E_i}{LD_b} \text{demand contribution of bus } b (MW) \qquad \qquad \delta_{bts} \text{voltage angle at} \\ \frac{P_i^{\min}}{RU_i/RD_i} \text{ramp up/down (MW/h)} \end{cases}$	1	E(<i>t</i> , <i>t</i> ')	elasticity of demand	14 int	integrated wind
$\frac{E_i}{LD_b} = \frac{1}{2} \frac{1}{10000000000000000000000000000000000$	1	<u>5m</u> i E	lower limit on the emission cost of unit $i(\$/n)$	VV st varcurt	integrated wind
$ \begin{array}{ccc} LD_b & demand contribution of bus b (MW) & \delta_{bts} & voltage angle at \\ P_i^{\min}/P_i^{\max} & \mininmum/maximum output limit (MW) \\ RU_i/RD_i & ramp up/down (MW/h) \end{array} $	1	<u>Ľi</u>	lower limit on the fuel cost of unit $l(s/n)$	VV _{st}	curtailed wind p
$P_i^{\text{inter}}/P_i^{\text{inter}}$ minimum/maximum output limit (MW) RU_i/RD_i ramp up/down (MW/h)	1	LD _b	demand contribution of bus b (MW)	0 _{bts}	voltage angle at
KU_i/KU_i ramp up/down (MW/h)	1	P_i^{n}/P_i^{n}	minimum/maximum output limit (MW)		
	1	KU_i/KD_i	ramp up/down (MW/n)		

In a tremendous share of the previous researches utilization of a storage device alongside wind farms has been suggested. Rabiee et al. [4] review various storage systems for wind power applications. In addition, Jannati et al. [5] compare the ability of four different types of the energy storage systems to mitigate wind power fluctuations. Zafirakis and Kaldellis [6] propose an optimization model to determine the rated power and capacity of a Compressed Air Energy Storage (CAES) to accommodate high wind power penetration in remote island networks. A dynamic optimization model is presented by Loisel [7], which simulates the key role of CAES under two development scenarios for European Commission (EC) and French Transmission System Operator (RTE) by 2030.

Combined operation of wind-hydrogen based, wind-flywheel based, and wind-pumped based energy storage systems are discussed by [8–10], respectively. Also, applying a hydro power plant as a supplemental unit beside wind farms is another solution which is taken into consideration for reducing the intermittent impacts of wind generation [11].

Another set of papers have proposed new market structures to facilitate wind power integration. Weber [12] discusses some key feature of the short-term adjustments required by wind energy and the necessity of intraday markets. The obtained results of a realistic case related to Australian National Energy Market (NEM) have been outlined in [13] which investigate policy and market design to facilitate wind integration. Other studies such as [14–16] investigate additional reserve capacity requirements for

SU/SD-	start-un	/shutdown	cost	of	unit	i	(\$)
$JU_i JU_i$	start-up	/ silutuo vvii	COSL	UI.	umu	ι	191

- wn time (h)
- ower (MW h)
- 1
- pation level in DRPs
- ue (\$/MW h)
- ver curtailment (\$/MW h)
- price (\$/MW h)

ind power scenario s

$C_{EDRP}(t)$	cost of customer's participation in EDRP (\$)
F _{lts}	power flow through line <i>l</i> in hour <i>t</i> of scenario <i>s</i> (MW)
I _{it}	binary status indicator of generating unit <i>i</i> in hour <i>t</i>
y_{it}/z_{it}	binary start-up/shutdown indicator of unit <i>i</i> in hour <i>t</i>
$P_{its}^{e}(m)$	generation of segment <i>m</i> in linearized fuel cost curve
	(MW h)
P_{bt}^{mod}	modified demand of bus <i>b</i> in hour <i>t</i> after implementing
	DR (MW)
P_{its}^{tot}	total scheduled power of unit <i>i</i> in hour <i>t</i> of scenario <i>s</i>
	(MW)
SR _{it}	scheduled spinning reserve of unit <i>i</i> in hour <i>t</i> (MW)
NSR _{it}	scheduled non-spinning reserve of unit <i>i</i> in hour <i>t</i> (MW)
sr _{its}	deployed spinning reserve of unit <i>i</i> in hour <i>t</i> of scenario
	s (MW h)
nsr _{its}	deployed non-spinning reserve of unit <i>i</i> in hour <i>t</i> of sce-
	nario s (MW h)
$q_{its}(m)$	generation of segment m in linearized emission curve
	(MW h)
$v_n(t)$	award of segment <i>n</i> in linearized total incentive curve in
•	hour t (\$/MW h)
W_{st}^{int}	integrated wind power in hour <i>t</i> of scenario <i>s</i> (MW h)
W_{st}^{curt}	curtailed wind power in hour t of scenario s (MW h)
δ_{bts}	voltage angle at bus b in hour t of scenario s (rad)

reliable grid integration of wind power through electricity market environment, belonging to the second category. It is worthy to note that, application of deterministic approaches in wind-thermal scheduling problems is not effective due to the stochastic behavior of wind generation. Hence, many recent papers focused on stochastic programming approaches as it has exerted in [15,16].

The third group of researches includes flexible demand side resources such as Plug in Hybrid Electric Vehicles (PHEVs) and Demand Side Management (DSM) solutions, particularly Demand Response (DR). Electric Vehicles (EVs) have been proposed as an option to alleviate the diversity between the electricity supply and demand in systems with high penetration of wind power as emphasized in [17–19]. In addition to EVs, some papers investigated the major role of DR in compensating wind power uncertainties. The possible impacts of DR on power system operation with high penetration of wind power have been analyzed in [20,21]. Many researches have been investigated to detail the impacts of DR on wind integration. Sioshansi and Short [22] evaluate the effects of a price-based DR program on the usage of wind power. Precisely, the impacts of Real-Time Pricing (RTP) implementation on increasing both the percentage of load that is served by wind generation, and potential wind generation is examined. In the paper, DR is implemented under a RTP tariff considering own price elasticity, only. Demand side resources have been considered in the form of peak clipping and demand shifting units with application to wind integration [23,24]. Parvania and Fotuhi-Firuzabad [25]

Download English Version:

https://daneshyari.com/en/article/765679

Download Persian Version:

https://daneshyari.com/article/765679

Daneshyari.com