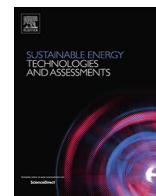




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Original article

## Frequency regulation capabilities in wind power plant

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## ABSTRACT

The design of frequency regulation services plays a vital role in automation and eventually reliable operation of power system at a satisfactory and stable level. Frequency response capability offered by wind plant is not same as the primary control capability of conventional plants, hence the integration of wind energy based generation at large scale has widespread impacts on power system stability and reliability. With the changing generation mix, modern electric power systems are facing a critical challenge in the real-time balancing of demand and supply. This paper comprehensively reviews the various control functionalities available in wind energy systems for supporting frequency regulation at different levels of frequency control services starting from inertial control to the secondary control. An insight to new research challenges for better frequency control ancillary services in wind integrated system is also provided. Though wind-based ancillary services are still in research and development stage in most of the countries, future wind energy system participation is expected to contribute to enhanced market efficiency, improved system reliability and macro economic benefits to all stakeholders.

## Introduction

Present power system is undergoing several changes in its core structure which are associated with the adoption of new power production technologies and rapid integration of Renewable Energy Sources (RES). There has been a tremendous increase in generated megawatts by the RES all over the world including Australia. There were 43 countries with Renewable Energy Target (RET) in 2005 which rose to 164 countries in 2015 [1]. Table 1 provides a comparison of RET for some of the countries. Proven and mature wind power technology has profoundly penetrated energy matrix at global level, hence among all available RES, maximum impact potential lies with wind energy at largest scale. Wind is the most cost competitive renewable source of electricity generation behind hydro. Share of wind and solar as primary renewable generation in electricity production for some of the countries in year 2016 is represented in Fig. 1. Energy is generated from wind in 79 countries around the world, and 24 of the countries have already installed capacity of more than 1000 MW by 2013 [2]. Denmark leads the world, followed by Sweden, Spain, and Germany [3] while Australia ranks 11th in the world for wind generation per capita ahead of countries like China and France. Among renewable energy sources, wind power had the fastest growth in Australia; increasing on average by 67% per year since 2000 [4]. There has been a steady increase in size and output power of wind turbines. Australia's first large-scale grid-connected wind farm (at Crook well, New South Wales) in 1998 comprised eight 600 kW wind turbines each with a rotor diameter of 44 m

for a combined energy output of 4.8 MW [4]. Today most onshore wind turbine generators have a capacity of 1.5–5 MW. The largest wind offshore turbines (IEC class S) at present is installed at Burbo Bank wind farm, U.K. Each turbine has a capacity of 8 MW, rotor blades of 262 feet length (80 m) and 195 m tower height [5] [6].

Design and operation of power system in presence of wind energy is one of the major issues in wind power integration. Renewable energy including wind power integration assessments are widely transformed now since their starting stage in late 1970s and early 1980s [17]. Literature presents wide difference in the viable penetration level of the intermittent generations in the power system. Technically, penetration level of wind energy system is dependent upon existing generation systems, their regulation capabilities, demand characteristic and correlation with resources [17,18]. Electrical system modelling including wind turbine technology and wind intermittency are the major factors contributing to the system integration effects [19]. Low penetration level and negative integration impacts are the strong reflection of simplistic and conservative assumptions and data input for wind-speed variations and spatial diversity in the wind integration studies [17]. Past studies raised the concerns that the integration of wind energy systems at large penetration level will have widespread technical impacts on power system stability and reliability. Studies showed that wind energy integration effects on system frequency and power fluctuation are nonzero and become more significant at higher sizes of penetrations [19–22]. Type-I, Type II, and Type-III (without auxiliary controls) wind turbines react weakly to frequency changes – hence,

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**Nomenclature**

ACE	Area Control Error	R	speed regulation or droop of governor
AGC	Automatic Generation Control	$R_{var}$	variable droop
AEMO	Australian Energy Market Operator	$M_{act}$	actual power margin available at a wind turbine
EMS	Energy Management System	$M_{max}$	maximum power margin available among all wind turbines
FCAS	Frequency Control Ancillary Service	$P_{AGC}$	power output from automatic generation control
MPPT	Maximum Power Point Tracking	$K_{pi}$	proportional time constant of AGC controller
ROCOF	Rate of Change of Frequency	$K_i$	integral time constant of AGC controller
SCADA	Supervisory Control and Data acquisition	$NI_A$	sum of the actual power flows on all tie lines or inter-connectors
TSO	Transmission System Operator	$NI_S$	sum of the scheduled flows on all tie lines or inter-connectors
VSWTG	Variable Speed Wind Turbine System	B	frequency bias setting
ROC	Renewable Obligation Certificate	$I_{ME}$	interchange (tie line) metering error
CPF	Causer Pays Factor	T- $\omega$ curve	torque-speed curve
AEMC	Australian Energy Market Commission	P- $\omega$ curve	power-speed curve
AWEFS	Australian Wind Forecasting System	$P_{ref-del}$	power set point for the de-loaded wind turbine
NWP	Numerical Weather Prediction	$\omega_{del}$	de-loaded wind turbine rotor speed
RTFDDA	Four-Dimensional Data Assimilation	$\omega_{meas}$	measured rotor speed for wind turbine
AEEGSI	Autorità per l'energia elettrica, il gas e il sistema idrico	$\omega_{opt}$	optimum rotor speed
MSD	Mercato Servizi di Dispacciamento	$P_{max}$	maximum mechanical power from turbine
CPS	Control Performance Standard	$P_{del}$	de-loaded Power
FLSR	Frequency Limited Sensitive Response	$K_{del}$	de-loading constant
FSR	Frequency Sensitive Response	$K_{opt}$	optimum mechanical power constant
WECC	Western Electricity Coordinating Council	$\beta_0$	pitch angle
FERC	Federal Energy Regulatory Commission	$\Delta\beta$	offset pitch angle
RET	Renewable Energy Target	$C_p$	turbine power coefficient
RES	Renewable Energy Source	$C_p(\lambda_{opt}, \beta)$	coefficient of power at optimum value of tip speed ration and pitch angle
ENTSO-E	European Network of Transmission System Operators for Electricity	$\lambda_i$	tip speed ratio at ith time step
UCTE	Union for the Co-ordination of Transmission of Electricity	$\rho$	air density
f	frequency	A	turbine blades swept area
$\frac{df}{dt}$	rate of change of frequency	R	blade length
$\Delta f$	frequency deviation	$V_{wind}$	velocity of the incident wind
$H_G$	inertia constant of conventional generating unit	$K_G$	system stiffness
$S_G$	MVA rating of conventional generating unit	$M_G$	inertia of power supply
W	kinetic energy of rotating mass	$P_{avail}$	available wind power
Hz/s	Hertz per second	v	wind speed
$L_p$	wind penetration level	DR <sub>cmd</sub>	derating command mode
J	moment of inertia of a rotating mass	$P_{ref}$	reference power setpoint
M	equivalent moment of inertia of all generators and the motors connected to the grid	$P_{operator}$	transmission system operator commanded power set point
$P_m$	generator mechanical power	$\omega_{ref}$	reference angular rotor speed
$P_e$	electrical load	$P_{APC}$	active power setpoint to turbine controller
$H_{eq}$	equivalent system inertia constant	$P_{final-ord}$	final power command provided to generator-converter model
$S_B$	system MVA base	$L_p$	wind penetration level
$S_{Gi}$	power rating of individual generating unit	$H_{WT}$	frequency responsive wind plant inertia
$\Delta P_{SG}$	change in active power output of synchronous generators in conventional generating plants	$T_d$	total time delay associated with generating unit model
$\omega_r$	angular speed	p.u.	per unit
$P_{primary}$	primary frequency control power	$P_{inertia}$	inertial power output from wind turbine

leads to smaller effective system inertia and degraded frequency response [23–25]. Increased penetration of old technology based wind generation in power system would, therefore necessitate a larger dependence on regulation ancillary services to return to normal operating conditions [26–28]. In contrast to technical impact studies, there are several techno-economic and social-economic modelling based recent research supporting 100% or near 100% renewable energy integration to grid [28–31]. 100% renewable energy for 139 countries including USA by 2050 is shown feasible by electrification of all applications which will reduce demand by 42% [32,33]. Even though most of these studies affirms that grid stability and security could be maintained under 100% renewable energy scenario by stronger network inter-connection [29] and coordination with flexible loads like electric car

[32,33], energy storage schemes [29,30] and efficient demand response [33,34], the result needs to be supported with satisfactory analysis of technical and economic implications. It is noticed from some of these studies that wind integration simulation studies based on hourly wind load data and production cost reflect higher penetration level while absence of cost production models for short term operational concerns like load frequency control gives lower penetration level.

Despite maximum elimination of interfacing concerns for wind energy and reducing technology costs, actual wind integration at this large scale is still challenging globally. Collective evaluation of fundamental technical, economic and regulatory challenges in a consistent framework is a requirement to ensure a safe, reliable, affordable, and sustainable future energy system. Given this discussion, this study aims

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