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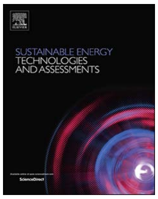

Original article

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
AGC	Automatic Generation Control
AEMO	Australian Energy Market Operator
EMS	Energy Management System
FCAS	Frequency Control Ancillary Service
MPPT	Maximum Power Point Tracking
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data acquisition
TSO	Transmission System Operator
VSWTG	Variable Speed Wind Turbine System
ROC	Renewable Obligation Certificate
CPF	Causer Pays Factor
AEMC	Australian Energy Market Commission
AWEFS	Australian Wind Forecasting System
NWP	Numerical Weather Prediction
RTFDDA	Four-Dimensional Data Assimilation
AEEGSI	Autorità per l'energia elettrica, il gas e il sistema idrico
MSD	Mercato Servizi di Dispacciamento
CPS	Control Performance Standard
FLSR	Frequency Limited Sensitive Response
FSR	Frequency Sensitive Response
WECC	Western Electricity Coordinating Council
FERC	Federal Energy Regulatory Commission
RET	Renewable Energy Target
RES	Renewable Energy Source
ENTSO-E	European Network of Transmission System Operators for Electricity
UCTE	Union for the Co-ordination of Transmission of Electricity
f	frequency
$\frac{df}{dt}$	rate of change of frequency
Δf	frequency deviation
H_G	inertia constant of conventional generating unit
S_G	MVA rating of conventional generating unit
W	kinetic energy of rotating mass
Hz/s	Hertz per second
L_P	wind penetration level
J	moment of inertia of a rotating mass
M	equivalent moment of inertia of all generators and the motors connected to the grid
P_m	generator mechanical power
P_e	electrical load
H_{eq}	equivalent system inertia constant
S_B	system MVA base
S_{Gi}	power rating of individual generating unit
ΔP_{SG}	change in active power output of synchronous generators in conventional generating plants
ω_r	angular speed
$P_{primary}$	primary frequency control power
R	speed regulation or droop of governor
R_{var}	variable droop
M_{act}	actual power margin available at a wind turbine
M_{max}	maximum power margin available among all wind turbines
P_{AGC}	power output from automatic generation control
K_{pi}	proportional time constant of AGC controller
K_i	integral time constant of AGC controller
NI_A	sum of the actual power flows on all tie lines or interconnectors
NI_S	sum of the scheduled flows on all tie lines or interconnectors
B	frequency bias setting
I_{ME}	interchange (tie line) metering error
T-ω curve	torque-speed curve
P-ω curve	power-speed curve
$P_{ref-del}$	power set point for the de-loaded wind turbine
ω_{del}	deloaded wind turbine rotor speed
ω_{meas}	measured rotor speed for wind turbine
ω_{opt}	optimum rotor speed
P_{max}	maximum mechanical power from turbine
P_{del}	deloaded Power
K_{del}	deloading constant
K_{opt}	optimum mechanical power constant
β_0	pitch angle
$\Delta\beta$	offset pitch angle
C_p	turbine power coefficient
$C_p(\lambda_{opt},\beta)$	coefficient of power at optimum value of tip speed ration and pitch angle
λi	tip speed ratio at ith time step
ρ	air density
A	turbine blades swept area
R	blade length
V_{wind}	velocity of the incident wind
K_G	system stiffness
M_G	inertia of power supply
P_{avail}	available wind power
v	wind speed
DR_{cmd}	derating command mode
P_{ref}	reference power setpoint
$P_{operator}$	transmission system operator commanded power set point
ω_{ref}	reference angular rotor speed
P_{APC}	active power setpoint to turbine controller
$P_{final-ord}$	final power command provided to generator-converter model
L_p	wind penetration level
H_{WT}	frequency responsive wind plant inertia
T_d	total time delay associated with generating unit model
p.u.	per unit
$P_{inertia}$	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 interconnection [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