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Review

The state of the art of wind energy conversion systems and technologies: A review

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ABSTRACT

This paper gives a comprehensive review of the state of the art of wind energy conversion systems (WECS) and technologies, with an emphasis on wind power generator and control. First, different types of common WECSs are classified according to their features and drive train types. The WECSs are compared on the basis of the volume, weight, cost, efficiency, system reliability and fault ride through capability. The maximum power point tracking (MPPT) control, which aims to make the generator speed meet an optimum value to ensure the maximum energy yield, plays a key role in the variable speed WECSs. A comprehensive review and comparison of the four most popular MPPT control methods are carried out and improvements for each method are presented. Furthermore, the latest development of wind energy conversion technologies is introduced, such as the brushless doubly fed induction generator (BDFIG), the stator permanent magnet synchronous generators, the magnetic-geared generators, dual power flow WECS with the electrical variable transmission (EVT) machine, and direct grid-connected WECS. Finally, the future trends of the technologies are discussed.

Contents

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Nomenclature

WECS	wind energy conversion system
SCIG	squirrel-cage induction generator
DFIG	doubly fed induction generator
SG	synchronous generator
PMSG	permanent magnet synchronous generator
EESG	electrically excited synchronous generator
MPPT	maximum power point tracking
MPP	maximum power point
TSR	tip speed ratio
HCS	hill climb searching
BDFIG	brushless doubly fed induction generator
WRIG	wound rotor induction generator
FL	fuzzy-logic
NN	neural network
MC	matrix converter
P&O	perturb & observe
WRBFN	Wilcoxon radial basis function network
TSK	Takagi–Sugeno–Kang
λ	tip speed ratio
P	wind mechanical power
v	wind velocity
ω	rotor speed
ω_{opt}	optimum rotor speed
P_{opt}	optimum wind mechanical power
k_{opt}	factor determined by the wind turbine characteristics
FRT	fault ride through
C-SCIG–MG	constant speed WECS with a SCIG and multiple-stage gearbox
DFIG–MG	variable speed WECS with a DFIG and multiple-stage gearbox
EESG–DD	direct-drive WECS with a EESG
PMSG–DD	direct-drive WECS with a PMSG
PMSG–1G	WECS with a PMSG and a single-stage gearbox
DFIG–1G	WECS with a DFIG and a single-stage gearbox
DSPM	doubly salient permanent magnet
FRPM	flux reversal permanent magnet
FSPM	flux switching permanent magnet
MG	magnetic gear
HTS	high temperature superconductor
EVT	electrical variable transmission
DPF	dual power flow
CFDR	constant-frequency double-rotor
PMIG	permanent magnet induction generator
SS-PMG	slip-synchronous permanent magnet generator
O&M	operation and maintenance
ρ	air density
R	radius of turbine blades
C_p	power coefficient
λ_{opt}	optimum tip speed ratio
$C_{p\,max}$	maximum power coefficient
T_{opt}	optimum wind mechanical torque

1. Introduction

Fossil fuel is the main energy resource of the worldwide economy, but the recognition of it as being a major cause of environment problems makes the mankind look for alternative energy resources. Then wind energy is becoming the world's fastest growing renewable energy, recorded an average growth of 21% in the past decades (Fig. 1). The new worldwide wind capacity at the end of 2013 reached 318,105 MW and contributed about 3% of the global electricity demand [1], due to the fact that it can be easily captured by wind generators with higher power capacity compared to other renewable energy sources [2,3]. Without doubt wind power has become a pillar of the energy systems in many countries and is recognized as a reliable and affordable source of electricity [4].

The development of wind energy conversion technology has been going on since 1970s and the rapid development has been seen from 1990s [5], especially in the last decade, stimulated by the high growth rate in the wind energy market. Hence, various new wind energy conversion technologies have been emerging, aiming at reducing cost, enhancing efficiency and reliability. The early wind energy conversion system (WECS) type is the constant speed WECS with a multiple-stage gearbox and a squirrel-cage induction generator (SCIG) which is connected to the grid directly. Due to the development of the power electronic technique, the variable speed WECS with a multiple-stage gearbox, a doubly fed induction generator (DFIG) and a partial-scale converter has been proposed to expand the system operation range of wind speed and increase the system efficiency [6,7]. Since the multiple-stage gearbox is vulnerable, the gearless direct-drive WECS with a synchronous generator (SG) and a full-scale converter has been developed. Then the permanent magnet synchronous generator (PMSG) is adopted to replace the traditional electrically excited SG (EESG) to improve the efficiency and reliability [3]. Currently, the variable