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Full Length Article

A nonlinear maximum power point tracking technique for DFIG-based wind energy conversion systems

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ABSTRACT

This paper presents a nonlinear control method for maximum power point tracking (MPPT) of doubly fed induction generator-based wind energy conversation systems. The proposed control structure is wind speed sensorless and independent from turbine characteristics and parameters such as optimal power-speed curve and optimum tip-speed-ratio. The presented MPPT scheme is designed based on adaptive backstepping control method and shown to be robust and stable against parametric uncertainties and wind speed disturbances. The validity, effectiveness and robustness of the proposed MPPT control method is demonstrated through simulation studies in the MATLAB® software environment.

1. Introduction

Reduction of at least 40% in emissions compared with 1990 levels and generation of at least 27% of the required electrical energy from clean resources, are of the most important targets of Climate and Energy package 2030 [1,2]. However, these objectives cannot be realized except by more than ever development of renewable energy sources such as solar, hydro and wind power. Among them, wind energy conversion systems (WECSs) have had the fastest growth and this trend is expected to continue for several decades [3].

In order to maximize the extracted energy from WECS, the wind turbine energy conversion efficiency should reach its maximum value. Therefore, tracking the maximum power of wind turbines has become one of the most important controls of WECSs. The ability of adjusting the rotor speed in order to seek the maximum turbine power and the capability of decoupling control of the output active and reactive power make the doubly fed induction generator (DFIG) based WECS one of the most used forms of these systems. Therefore, control of DFIG-based WECSs with the objective of maximum power point tracking (MPPT) has become an attractive topic [4].

In order to perform MPPT, the WECS is required to be equipped with a suitable controller and an optimization algorithm. So far, various MPPT methods have been proposed in the literature. The most commonly used methods are power signal feedback (PSF) control [5], optimal torque (OT) control [6], and tip speed ratio (TSR) control method [7]. The PSF control method is based on characteristic curve of the turbine optimum mechanical power versus wind speed, provided by the manufacturer, offline experiments, or simulations, for a given wind turbine. Using this curve, the generator reference power is determined to perform MPPT for a given wind speed. The OT control method is based on the trajectory of the optimum mechanical torque, described by a quadratic function of turbine speed. In this method, the generator reference torque is determined by multiplying the square of rotor speed in an optimal coefficient. In TSR control method, the generator reference speed is determined for a given wind speed based on an optimal TSR value. However, a challenging issue is that these methods are significantly relying on the turbine characteristics, and may fail under uncertainties caused by variation in the environmental conditions (such as density, temperature and humidity of the air), contamination and aging of the blades, and wind speed natural fluctuations [3,4], [8–12].

In order to overcome these drawbacks, the characteristic-independent methods such as perturbation and observation (P&O), Hill-climbing search (HCS), fuzzy logic control (FLC), artificial neural network (ANN), and hybrid methods have attracted research efforts [13–16]. The P&O and HCS methods are basically applied for MPPT in photovoltaic systems. In these methods, MPPT is performed through adding a perturbation to the rotor speed reference signal and observing the sign of the extracted power

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Nomenclature

Abbreviation

ANN	artificial neural network
DFIG	doubly fed induction generator
FLC	fuzzy logic control
GSC	grid side converter
HCS	Hill-climbing search
MPPT	maximum power point tracking
OTC	optimal torque control
PSF	power signal feedback
P&O	perturbation and observation
RSC	rotor side converter
TSR	tip speed ratio
WECS	wind energy conversion system

Turbine-DFIG variables

ρ	air density
C_p	power coefficient
λ	tip-speed ratio
β	blade pitch angle
R_b	blade radius
υ_w	wind speed
ω_t	turbine shaft mechanical speed
ω_m, ω_r	rotor shaft mechanical, electrical speed
T_m, T_e	mechanical, electromagnetic torques
Q_s	stator reactive power
H_m	lumped inertia constant
D	lumped damping factor
R_s, R_r	stator, rotor resistances
L_s, L_r	stator, rotor inductances
L_m	magnetizing inductance
σ	leakage factor
p	pole pairs

DFIG vector variables

$\boldsymbol{\psi}_s, \boldsymbol{\psi}_r$	stator, rotor flux linkages
$\mathbf{i}_s, \mathbf{i}_r$	stator, rotor currents
$\mathbf{v}_s, \mathbf{v}_r$	stator, rotor voltages

Control system variables

V	Lyapunov function
e	tracking error
k	control gain
ξ	lumped uncertainty
γ	estimation gain

gradient. However, convergence dependency on the initial operating point, interference of power changes due to wind speed fluctuation and reference signal perturbation, sensitivity to noise and perturbation signal form, and near-optimal oscillations, are the main disadvantages of the P&O and HCS methods [3,4,12].

The FLC method combines tacit knowledge with explicit knowledge and, without the need for accurate system modeling, can adaptively track MPP of the wind turbines based on a series of if-then rules. Nevertheless, the design and adjustment of such controllers is complex and the effectiveness largely depends on the knowledge and experience of the user. In ANN method, an interconnected and multilayered group of artificial neurons, after proper offline training based on turbine characteristic data, is used for tracking of wind turbine MPP. However, the performance of the method greatly depends on the quality of initial training and the quantity of topological designing [12]. The hybrid methods integrate FLC with ANN to take the advantages of both methods [10]. However, the large number of if-then rules and parameters that must be trained is the main problem of these methods [17].

Since DFIG-based WECSs are strongly nonlinear and have many parametric uncertainties, nonlinear MPP tracking control methods have also been developed in recent years [18]. In [19], a nonlinear MPP tracking control method has been presented based on Lyapunov control theory, in which the TSR of turbine is forced to follow its optimal value. In [20,21], the optimal rotor speed is obtained online, using the optimum TSR of a wind turbine and the measured wind speed. In [20] based on backstepping control method, and in [21] based on feedback linearization control method, the rotor speed has been then controlled to follow the obtained optimal reference. However, measuring the wind speed is a prerequisite for these methods.

In order to track the MPP of a wind turbine, the system nonlinearities and uncertainties are estimated, the optimal rotor speed is determined based on a numerical method, and an adaptive sliding mode based control method is presented in [22]. In [23], the optimal rotor speed corresponding to MPP of a wind turbine is adaptively estimated a feedback control method and tracked based on a Lyapunov control theory. In [24], an adaptive backstepping speed controller is presented for a variable speed WECS, which is modeled only as a drive-train system. However, the presented methods in [22–24] are effective only for slow variation of the wind speed. Based on Lyapunov theory, the power coefficient of a wind turbine is estimated in [25] and the optimum rotor speed determined from derivative of power coefficient is followed to perform MPPT.

The main contribution of this paper is to propose a wind speed-sensorless control structure based on adaptive backstepping method to track the MPP of DFIG-based WECSs. The presented control method is independent from turbine characteristics such as optimal power-speed curve and optimum TSR. The proposed method is shown to be robust and stable against parametric uncertainties and wind speed disturbances. The validity and effectiveness of presented method is demonstrated through simulation studies in the MATLAB® software environment.

2. Dynamic modelling of DFIG-based WECS

Fig. 1 shows a schematic diagram of the DFIG-based WECS consists of a wind turbine, a DFIG, and a back-to-back converter. In this system, the wind turbine is mechanically coupled to the DFIG through a gearbox and shaft system. While the rotor of DFIG is fed through back-to-back converter, the stator is directly connected to an infinite bus. The back-to-back converter is consists of a grid side converter (GSC) and a rotor side converter (RSC), which are connected via a DC link. Since the dynamics of the wind

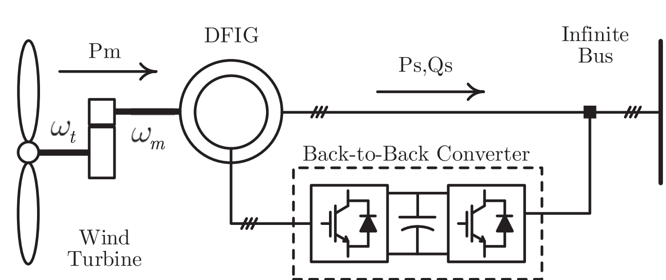

Fig. 1. Schematic diagram of the DFIG-based WECS.

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