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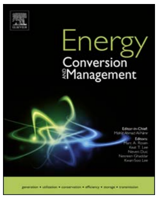

Democratic joint operations algorithm for optimal power extraction of PMSG based wind energy conversion system

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ABSTRACT

This paper proposes a novel military philosophy inspired meta-heuristic algorithm called democratic joint operations algorithm (DJOA), which attempts to find the optimal parameters of proportional-integral-derivative (PID) controllers of permanent magnetic synchronous generator (PMSG) based wind energy conversion system (WECS), such that a maximum power point tracking (MPPT) under different wind speed profiles can be achieved. In order to realize a deeper optimum search, an additional deputy officer is introduced into the democratic defensive operations of each military unit, in which the soldiers can wisely seek a more optimal defensive position following the consensus/compromise of the officer and deputy officer. Furthermore, the shuffling strategy of shuffled frog leaping algorithm (SFLA) is employed for the shuffling regroup operations of DJOA, which effectively avoids the local optimum trapping by sharing the global position information among all the soldiers. Three case studies are carried out, e.g., step change of wind speed, low-turbulence stochastic wind speed variation, and high-turbulence stochastic wind speed variation, respectively. Simulation results verify that an improved optimal power extraction can be realized by DJOA compared with that of other five typical meta-heuristic algorithms.

1. Introduction

In the past decade, the astonishing global population booming and continuous fossil fuel depletion have driven considerable social and industrial demands of renewable energy, e.g., solar, wind, hydro, tidal, biomass, geothermal, etc., among which wind energy conversion system (WECS) deployment is in an amazingly fast expansion, whether onshore or offshore, given the promising economic merits of wind power and the increased competitiveness regarding other sources of electrical energy [1]. So far, WECS mainly contains two groups of generators, i.e., doubly-fed induction generator (DFIG) [2] and permanent magnet synchronous generator (PMSG) [3]. Currently, the application of PMSG has been noticeably increased thanks to its elegant advantages of simple structure, efficient energy production, gearless construction, self-excitation, and low noise [4]. In practice, a major task of PMSG controller is to extract the mechanical power at various wind speed as much as possible, also known as maximum power point tracking (MPPT) [5]. At the moment, conventional vector control (VC) using classical proportional-integral-derivative (PID) loops are widely employed to design the control system of PMSG with the prominent features of operation reliability and structure simplicity [6]. Although fractional-order PI/PID control could be employed to improve the dynamical performance by introducing two additional control parameters [7], one inherent weakness of such control framework is its inconsistent control performance when operation condition varies due to the one-point linearization, such issue becomes especially severe in the face of PMSG as wind speed usually changes in a highly stochastic and fast time-varying pattern [8].

Generally speaking, two main types of methodology have continuously endeavoured to tackle this thorny obstacle, e.g., nonlinear robust/adaptive control and meta-heuristic algorithms. The former one aims to fully/partially remove the system nonlinearities to achieve a globally consistent control performance or to introduce various robust/adaptive mechanisms to efficiently handle the unmodelled dynamics, parameter uncertainties, external disturbances, etc. [9]. In Refs. [10,11], a feedback linearization control (FLC) was proposed to fully compensate all system nonlinearities of PMSG for MPPT, which however requires an accurate system model. In order to enhance system robustness against modelling uncertainties and to improve total harmonic distortion property, a sliding-mode control (SMC) scheme was

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Nomenclature

Variables

v_{wind}	wind velocity
ρ	air density
R	turbine radius
C_P	power coefficient
C_{Pmax}	maximum power coefficient
λ	tip-speed-ratio
λ_{opt}	optimal tip-speed-ratio
β	blade pitch angle
T_e	electromagnetic torque
T_m	mechanical torque
Q_s	stator reactive power
P_s	stator active power
ω_s	synchronous angle speed
ω_r	rotor angular speed
ω_b	electrical base speed
i_{dr}, i_{qr}	dq-axis rotor currents
i_{ds}, i_{qs}	dq-axis stator currents
V_d, V_q	dq-axis control inputs
T_e	electromagnetic torque
Ψ_{sd}, Ψ_{sq}	dq-axis fluxes
Ψ_f	flux linkage

System parameters

σ	the leakage coefficient
R_s, R_r	stator and rotor resistances
L_s, L_r	stator and rotor inductances
L_m	magnetizing inductance
J_{tot}	total inertia of the drive train
p	pole pairs
D	damping coefficient
v'_{sd}, v'_{sq}	dq-axis compensation terms

Abbreviations

PMSG	permanent magnetic synchronous generator
GA	genetic algorithm
PSO	particle swarm optimization
WECS	wind energy conversion system
JOA	joint operation algorithm
DJOA	democratic joint operation algorithm
PID	proportional-integral-derivative
QGA	quantum genetic optimization algorithm
MPPT	maximum power point tracking
BLPSO	biogeography-based learning particle swarm optimization
AG	approximate gradient
SLFA	shuffled frog leaping algorithm

PID control parameters

K_{P1}	proportional gain of rotor speed
K_{I1}	integral gain of rotor speed
K_{D1}	derivative gain of rotor speed
K_{P2}	proportional gain of q-axis current
K_{I2}	integral gain of q-axis current
K_{D2}	derivative gain of q-axis current
K_{P3}	proportional gain of d-axis current
K_{I3}	integral gain of d-axis current
K_{D3}	derivative gain of d-axis current

designed with an enhanced exponential reaching law [12]. Moreover, a nonlinear Luenberger-like observer was employed to estimate the mechanical variables by only the measurement of electrical variables of PMSG to achieve MPPT [13]. Besides, an artificial neural network (ANN)-based reinforcement learning (RL) was adopted to enable the PMSG to behave like an intelligent agent with memory to learn from its own experience, thus the MPPT learning efficiency could be greatly improved [14]. In addition, a nonlinear backstepping approach based on Lyapunov theory was reported in Ref. [15], which is able to accurately track the optimal power curve under various wind speed. Furthermore, an active disturbance rejection control (ADRC) scheme was devoted to reject both the internal and external disturbances of PMSG to capture the maximum power from the wind [16].

On the other hand, an enormous variety of meta-heuristic algorithms have been proposed with different variants/modifications to resolve plenty of complex and complicated management or engineering problems, which are, in essence, inspired from the millions year of extraordinarily competitive biological evolution in the harsh nature (evolutionary algorithm) or elaborately emulate the efficient collective behaviours of animals, insects, or human society (swarm-based algorithm) [17]. A genetic algorithm (GA) was applied on PMSG to optimally adjust proportional-integral (PI) control parameters considering both symmetrical and unsymmetrical faults, as well as the permanent fault condition due to unsuccessful reclosing of circuit breakers [18]. In work [19], a particle swarm optimization (PSO) was used to improve the control performance of PMSG under various wind speed via tuning the PI control parameters. Besides, a firefly algorithms (FA) was studied for the optimal PID control parameters tuning of pitch angle controller of PMSG, such that a stable and optimal power tracking could be realized [20]. Additionally, an adaptive ant colony optimization (AACO) was incorporated with general regression neural network for MPPT of WECS [21]. Meanwhile, a modified honey bee mating optimization (HBMO) algorithm was investigated for the optimal placement of renewable electricity generators, in which the transmission losses, costs of electrical generation and voltage deviation of photovoltaic units, wind turbine and fuel cell units are simultaneously considered [22]. Moreover, literature [23] reported a gradient-based multi-objective optimization algorithm using nonlinear mathematical programing to solve the multi-objective wind farm layout optimization. Besides, a bacterial foraging algorithm (BFA) was employed which attempts to accommodate high penetrations of wind power with the integration of battery energy storage system based on an economic dispatch model [24].

Thus far, how to effectively and efficiently obtain the global optimum of practical engineering problems still remains to be an extremely challenging and crucial task due to the ubiquitous difficulties of high dimensionality, multimodality, non-differentiability, and ill-conditioning. Recently, a human society behaviour inspired meta-heuristic algorithm called joint operations algorithm (JOA) has been developed to meticulously mimic the military philosophy of joint operations of multiple military units in battles, of which three important operations, e.g., offensive operations (global exploration), defensive operations (local exploitation), and regroup operations (re-organization strategy), are introduced to cooperatively deal with the annoying dilemma when the optimization algorithms are trapped at local optimum [25]. Based on the aforementioned principle, this paper proposes a novel democratic joint operations algorithm (DJOA), which aims to further enhance the global exploration ability and local exploitation ability of the original JOA associated with the following two promising characteristics:

- A democratic defensive operations is formed via the introduction of an additional deputy officer into each military unit, such that a