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Grouped grey wolf optimizer for maximum power point tracking of doubly-fed induction generator based wind turbine

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ABSTRACT

This paper proposes a novel grouped grey wolf optimizer to obtain the optimal parameters of interactive proportional-integral controllers of doubly-fed induction generator based wind turbine, such that a maximum power point tracking can be realized together with an improved fault ride-through capability. Under the proposed framework, the grey wolves are divided into two independent groups, including a cooperative hunting group and a random scout group. The former one contains four types of grey wolves (i.e., alpha, beta, delta, and omega) to accomplish an effective hunting based on their hierachical cooperation and three elaborative maneuvers in the presence of an unknown environment, e.g., prey searching, prey encircling, and prey attacking, of which the number of beta and delta wolves is increased to achieve a deeper exploitation. On the other hand, the latter one undertakes a randomly global search and realizes an appropriate trade-off between the exploration and exploitation, thus a local optimum can be effectively avoided. Three case studies are carried out which verify that a better global convergence, more accurate power tracking and improved fault ride through capability can be achieved by the proposed approach compared with that of other heuristic algorithms.

1. Introduction

Nowadays, severe environmental problems such as global warming, air pollution caused by the extensive use of fossil fuels have drawn the world's attention to renewable energy utilization [1]. The wind power has been developed rapidly for its significant advantages of cleanness and resource abundancy [2], which attracts an enormous variety of studies and researches due to the ever-increasing concern about CO_2 emissions [3]. Especially in the last decade, mainly stimulated by the high growth rate in the global wind energy market. The power rating of wind turbines is growing thanks to the use of doubly-fed induction generator (DFIG) and advanced power electronic converters, while DFIG has become one of the most popular wind power generation systems and widely installed in industry due to its elegant merits of high energy conversion efficiency under variable wind speeds, four-quadrant active and reactive power capabilities, relatively low cost of power electronic converters, and lower power losses compared to that of a system based on a fully fed synchronous generator with full-rated converters [4].

Maximum power point tracking (MPPT) is one of the main control objectives applied below the rated wind speed, which attempts to extract the optimal power of the wind turbine for various wind speeds [5]. As DFIG has strong nonlinearities and uncertainties originated from the aerodynamics of wind turbines and unpredictable wind energy penetration, many nonlinear or adaptive approaches have been developed to remedy this issue. An improved Elman neural network (ENN) was developed to achieve a fast and stable response for the real power control [6]. Perturbation and observation (P&O) method was proposed in [7] to overcome the rapidity/efficiency trade-off and the divergence from peak power under a fast variation of the wind speed. Additionally, a feedback linearization controller was presented in [8] to achieve a global optimal power tracking over various wind operation range, in which the modal analysis was employed to thoroughly investigate the closed-loop system performance as well as the internal dynamics stability. Furthermore, Ref. [9] designed an internal model state-feedback control, such that a smooth control signal of the conventional proportional-integral (PI) controller can be maintained with a significant robustness against to external disturbances. Moreover, a sliding mode controller was applied to achieve an active and reactive power control, with P&O being adopted for an optimal power tracking [10]. Besides, a nonlinear backstepping

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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	reactive power
s	generator slip
ω_s	synchronous angle speed
ω_r	rotor angular speed
ω_b	electrical base speed
i_{dr}, i_{qr}	dq-axis rotor current
i_{ds}, i_{qs}	dq-axis stator current

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
H_g	generator inertia
H_t	turbine inertia
D	damping coefficient

Abbreviations

DFIG	doubly fed induction generator
GA	genetic algorithm
PSO	particle swarm optimization
GWO	grey wolf optimizer
MFO	moth-flame optimization
GGWO	grouped grey wolf optimizer
PI	proportional-integral
VC	vector control
MPPT	maximum power point tracking

PI parameters

K_{iwr}	integral gain of rotor speed
K_{pwr}	proportional gain of rotor speed
K_{iIq}	integral gain of q-axis current
K_{pIq}	proportional gain of q-axis current
K_{iQ}	integral gain of reactive power
K_{pQ}	proportional gain of reactive power
K_{iId}	integral gain of d-axis current
K_{pId}	proportional gain of d-axis current

strategy was used in [11] for MPPT, whose global asymptotic stability was proved in the context of Lyapunov theory. Meanwhile, literature [12] proposed a nonlinear backstepping adaptive control to provide a great robustness of MPPT, which effectiveness was validated by FPGA.

However, the control structure of the aforementioned approaches is relatively complicated, which may not be easy to be realized in practice. Vector control (VC) associated with PI controllers has been widely recognized and applied in industry for a rapid and reliable power regulation of DFIG thanks to its capability of a decoupling control of active/reactive power and a simple structure [13]. In general, the control performance of VC largely depends on a proper tuning of PI parameters, the accuracy of machine parameters, the voltage conditions of the connected power grid, the random wind speed variation, and different operating points. Usually, the PI parameters of DFIG is manually tuned based on a specific operating point of the linearized model of the original nonlinear DFIG systems, which control performance may be dramatically degraded as the operating condition often varies. As a result, reliable and efficient optimization approaches are needed to optimally tune the PI parameters with the consideration of various operating conditions. It has been found that conventional gradient based optimizations may fail to obtain the optimal parameters resulting from their high dependence of an accurate system model, such as Newton and interior point method. Hence, several heuristic algorithms have been developed to tackle the above challenges, such that an efficient global search can be achieved with a lower dependence of the accurate system model, e.g., a particle swarm optimization (PSO) is designed in [14] to ensure an MPPT of DFIG through an indirect power control, which leads to a less error criteria of performance index compared with that of the manually tuned PI controller; The fuzzy logic sensorless MPPT is developed by [15] to increase the DFIG's reliability by reducing the converter losses, which can provide the same output electric power with a smaller size of power converter; Moreover, Ref. [16] applies differential evolutionary algorithm (DE) to improve the DFIG performance during disturbance; In addition, a modified bacterial foraging algorithm (BFA) is employed in [17] to maintain the voltage secure operation with reduction in wind-thermal generation system loss, in which the chemotaxis and swarming stages are modified to accelerate the convergence rate; Furthermore, genetic algorithm (GA) is adopted for the fault ride-through of DFIG without the use of any auxiliary hardware [18], which follows the original search mechanisms including reproduction, crossover, and mutation. Nevertheless, the above approaches are relatively prone to reach a premature convergence due to the inefficient exploitation and exploration, hence the global optimal PI parameters of DFIG might not be readily obtained.

Recently, a meta-heuristic algorithm called grey wolf optimizer (GWO) mimicking the social (leadership) hierarchy and hunting behaviours of grey wolves in the wild nature was developed by [19], of which four types of grey wolves (alpha, beta, delta, and omega) are employed to roughly simulate the leadership hierarchy evolved from the struggling for existence of the whole species. It has been observed that three elaborative maneuvers, e.g., prey searching, prey encircling, and prey attacking, are frequently adopted to perform a collaborative hunting, which has been clearly elaborated in [20]. Basically, GWO has the following three prominent advantages: (i) efficient exploitation and exploration; (ii) effective local optimum avoidance; and (iii) favourable performance in the presence of an unknown environment, thus it can achieve a dramatic improvement of global optimization compared to that of other typical heuristic algorithms, e.g., a gravitational search algorithm (GSA) [21] is used to design an adaptively fast fuzzy fractional order PID controller for pumped storage hydro unit; Meanwhile, a differential evolution (DE) based multi-objective optimization algorithm is proposed to optimally size a photovoltaic water pumping system [22]; additionally, an artificial bee colony algorithm is used as a local search procedure while the evolutionary programming (EP) is applied to refine the feasible

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