OPTIMAL TUNING OF FIXED SPEED WIND TURBINES PITCH CONTROLLER USING GREY WOLF OPTIMIZER

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ABSTRACT

The world is facing global warming due to the burning of fossil fuels to generate electricity. Therefore, Renewable Energy Sources (RES) such as wind turbines are integrated into the power system to reduce global warming. But the large-scale integration of the wind turbines into the power system can cause instability in the system due to intermittency in their outputs. Therefore, the wind turbine Proportional Integral (PI) based pitch controls are typically applied to enhance the generated power and the dynamic stability of the outputs. But, the PI controller's gains in the pitch controls have to be tuned to further enhance the generated power and dynamic stability of the outputs. In this study, the Grey Wolf Optimizer (GWO) is proposed to tune the PI gains of the pitch controls as a better tuning technique than the Particle Swarm Optimization (PSO) which has slow convergence speed, the Genetic Algorithm (GA) which has premature convergence and the Zeigler Nichols (ZN) tuning technique which has high overshoot. Also, the modification of the updating mechanism of the GWO is proposed to improve the GWO convergence speed and provide better PI gains of the pitch controls. The implementation of the PI gains of pitch controls obtained using the GWO in the pitch controls of the fixed speed and DFIG wind turbines is to show the GWO can enhance the generated power and the dynamic stability of the wind turbines. The tuning model for the PI pitch control was developed based on the Integral Time multiplied Square Error (ITSE) objective function with the PI gains as constraints. The tuning of the PI gains of the pitch control was conducted by minimizing the objective function using the GWO, the modified GWO, the PSO and the GA. The proposed modified GWO was validated through a comparison of its tuning result with the tuning results of the GWO, PSO and GA. The GWO and the modified GWO provided the least value of the objective function than the PSO and the GA. Additionally, the modified GWO exhibited faster convergence speed and provided better PI pitch control gains than the GWO, PSO and GA. Furthermore, the GWO, PSO, GA and ZN tuned gains were implemented in the PI pitch controls of fixed speed and DFIG wind turbines connected to the distribution system in four case studies. In the first case study, a 3MW fixed speed wind turbine connected to a 22.9 kV distribution line, and a 12.5 m/s average wind speed was used to run the wind turbine aimed to test the tuned PI controllers in the pitch control. In the second case study, a unit step increase above rated wind speed was applied to test the tuned PI pitch controllers in the 8x3MW fixed speed wind turbines connected as a wind farm with a 9 Bus IEEE stability test feeder. For the third and fourth case studies, a unit-step decrease in the pitch control nominal power and consecutive unit-step increases above rated wind speed respectively were applied, to test the tuned PI pitch controllers of DFIG wind turbines connected to a 9 Bus IEEE stability test feeder. The result from the first case study shows the GWO tuning of pitch control enhanced the generated power generation of the 3MW fixed speed wind turbine by 3.04 % compared to PSO, GA and ZN tuning techniques. For case studies, two to four, the GWO tuning of pitch controls enhanced the dynamic stability of fixed speed and the DFIG wind turbine outputs compared to the PSO, GA and ZN tuning techniques. The dynamic stability of the wind turbine outputs provided by the GWO tuning of PI pitch controls can reduce the stress on the pitch systems of the wind turbines.

ABSTRAK

Dunia menghadapi pemanasan global kerana pembakaran bahan bakar fosil untuk menjana elektrik. Oleh itu, Sumber Tenaga Boleh Diperbaharui (RES) seperti turbin angin disepadukan ke dalam sistem kuasa untuk mengurangkan pemanasan global. Tetapi penyepaduan turbin angin secara besar-besaran ke dalam sistem kuasa boleh menyebabkan ketidakstabilan di dalam sistem disebabkan oleh kuasa keluaran yang tidak menentu. Oleh itu, turbin angin kamiran (PI) berkadar berasaskan kawalan pic biasanya digunakan untuk meningkatkan kuasa yang dijana dan kestabilan dinamik keluaran. Tetapi, gandaan pengawal PI di dalam kawalan pic perlu ditala untuk meningkatkan lagi kuasa yang dihasilkan dan kestabilan dinamik keluaran. Dalam kajian ini, Pengoptimum Grey Wolf dicadangkan untuk menala gandaan PI bagi kawalan pic sebagai teknik penalaan yang lebih baik daripada Pengoptimum Kerumunan Zarah yang mempunyai kelajuan penumpuan yang perlahan, Algoritma Genetik (GA) yang mempunyai teknik penumpuan pramatang dan penalaan Zeigler Nichols (ZN) yang mempunyai terlajak yang tinggi. Juga, pengubahsuaian mekanisme pengemaskinian GWO dicadangkan untuk meningkatkan kelajuan penumpuan GWO dan memberikan gandaan PI yang lebih baik bagi kawalan pic. Pelaksanaan kawalan pic gandaan PI yang diperoleh menggunakan GWO dalam kawalan pic bagi turbin angin kelajuan tetap dan DFIG adalah untuk menunjukkan GWO dapat meningkatkan kuasa keluaran yang dihasikan dan kestabilan dinamik turbin angin. Model penalaan untuk kawalan pic PI telah dibina berdasarkan fungsi objektif Kamiran Masa Berganda Ralat Kuasa Dua (ITSE) dengan gandaan PI sebagai kekangan. Penalaan gandaan PI dari kawalan pic dilakukan dengan meminimumkan fungsi objektif menggunakan GWO, GWO yang diubahsuai, PSO dan GA. GWO yang diubah suai yang telah dicadangkan, telah pun disahkan melalui perbandingan hasil penalaannya dengan hasil penalaan GWO, PSO dan GA. GWO dan GWO yang diubahsuai memberikan nilai fungsi objektif yang paling sedikit berbanding PSO dan GA. Tambahan itu, GWO yang diubahsuai memperlihatkan kelajuan penumpuan yang lebih cepat dan memberikan gandaan kawalan pic PI yang lebih baik daripada GWO, PSO dan GA. Tambahan pula, gandaan-gandaan yang ditala bagi GWO, PSO, GA dan ZN telah dilaksanakan dalam kawalan pic PI bagi turbin angin yang kelajuan tetap dan DFIG yang disambungkan ke sistem pengagihan dalam empat kajian kes. Dalam kajian kes pertama, turbin angin berkelajuan tetap 3MW disambungkan ke talian pengagihan 22.9 kV, dan purata kelajuan angin 12.5 m/s telah digunakan untuk menjalankan turbin angin yang bertujuan untuk menguji pengawal PI yang diselaraskan dalam kawalan pic. Dalam kajian kes kedua, peningkatan unit langkah yang melebihi kelajuan angin terkadar telah digunakan untuk menguji pengawal pic PI yang ditala dalam turbin angin berkelajuan tetap 8x3MW yang disambungkan sebagai ladang angin dengan penyuap ujian kestabilan 9 Bas IEEE. Untuk kajian kes ketiga dan keempat, penurunan langkah-unit di dalam kawalan pic kuasa nominal dan kenaikan langkah-unit secara berturut-turut melebihi kelajuan angin terkadar masing-masing telah dilaksana untuk menguji pengawal pic PI yang diselaraskan dari turbin angin DFIG yang disambungkan ke 9 IEEE Bas penyuap ujian kestabilan. Hasil kajian kes pertama menunjukkan penalaan kawalan pic GWO telah meningkatkan penjanaan kuasa turbin angin berkelajuan tetap 3MW sebanyak 3.04% berbanding teknik penalaan PSO, GA dan ZN. Untuk kajian kes, dua hingga empat, penalaan kawalan pic GWO telah meningkatkan kestabilan dinamik bagi turbin angin berkelajuan dan DFIG berbanding teknik penalaan PSO, GA dan ZN. Kestabilan dinamik bagi keluaran turbin angin yang disediakan oleh penalaan GWO kawalan pic PI dapat mengurangkan tekanan pada sistem pic turbin angin.

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LIST OF ABBREVIATIONS

ABC - Artificial Bee Colony
AC - Adaptive Controller
AC/DC - Alternative Current to Direct Current
AGC - Automatic Gain Control
AGWO - Advanced Grey Wolf Optimizer
ACL - Actor-Cretic Learning
ACO - Ant Colony Algorithm
AGC - Automatic Gain Control
AIGA - Advanced Intelligent Genetic Algorithm
ANFIS - Artificial Neuron Fuzzy Inferential System
ANN - Artificial Neuron Network
ANTA - Adaline Neuron Training Algorithm
AVR - Automatic Voltage Regulator
BA - Bat Algorithm
BBO - Bio-geography Based Optimization
BIBO - Bounded Input Bounded Output
BEM - Blade Element Momentum
BESS - Battery Energy Storage System
BFA - Bacteria Foraging Algorithm
BFOA - Bacteria Foraging Optimization Algorithm
BLDC - Brushless Direct Current
BSA - Backtracking Search Algorithm
CHP - Combine Heat Power
CSTP - Concentrating Solar Thermal Power
CSTR - Continuous Stirred Tank Reactor
CR - Combine Renewable
DA - Dragonfly Algorithm
DC - Direct Current
DE - Differential Evolution
DFIG - Doubly Fed Induction Generator

DG - Distributed Generation
DS - Dynamic Stability
DSO - Direct Search Optimization
DVR - Dynamic Voltage Restorer
DTC - Direct Torque Control
EMTDC - Electromagnetic Transients including DC
FA - Firefly Algorithm
FAST - Fatigue, Aerodynamics, Structures and Turbulence
FEP - Fast Evolutionary Programming
FLC - Fuzzy Logic Controller
FPIC - Fuzzy Proportional Integral Controller
FRT - Fault Ride Through
GA - Genetic Algorithm
GGWO - Group Grey Wolf Optimizer
GSA - Gravitational Search Algorithm
GW - Gigawatt
GWO - Grey Wolf Optimizer
IAE - Integral Absolute Error
ICA - Imperialist Competitive Algorithm
IEEE - Institute of Electrical and Electronics Engineering
IETC - International Electro-technical Commission
IGA - Improved Genetic Algorithm/Intelligent Genetic Algorithm
IM - Induction Motor
ICA - Imperialist Competitive Algorithm
ISE - Integral Square Error
ITAE - Integral Time multiplied Absolute Error
ITSE - Integral Time multiplied Square Error
KHA - Krilll Herd Algorithm
LFC - Load Frequency Control
LQR - Linear Quadratic Regulator
LVRT - Low Voltage Ride Through
MATLAB- - Matrix Laboratory
Max - Maximum

MGWO - Modified Grey Wolf Optimizer
Min - Minimum
MFO - Moth-Flame Optimization
MPPT - Maximum Power Point Tracking
MRS - Modern Renewable Sources
MSE - Mean Square Error
MVA - Mega Volt Ampere
NMO - Nelder’s Mead Optimizer
NREL - National Renewable Energy Laboratory
OS - Overshoot
PCC - Point of Common Coupling
PEV - Plug-in Electric Vehicle
PID - Proportional Integral Derivative
PI-GWO - Proportional Integral-Grey Wolf Optimizer
PLC - Programmable Logic Controller
PMSG - Permanent Magnet Synchronous Generator
PS - Pattern Search
PSCAD - Power Systems Computer-Aided Design
PSO - Particle Swarm Optimization
QOGWO - Quasi-Oppositional Grey Wolf Optimizer
RBF - Radial Basis Function
RES - Renewable Energy Sources
RGWO - Resultant Grey Wolf Optimizer
RL - Load Resistance
RST - Reference Signal Tracking
SA - Simplex Algorithm/Simulated Annealing
SCIG - Squirrel Cage Induction Generator
SG - Synchronous Generator
SGA - Standard Genetic Algorithm
SMIBS - Single Machine Infinite Bus System
SSA - Salp Swarm Algorithm
SSC - Stator Side Converter
TFEC - Total Final Energy Consumption

TLBO	-	Teaching Learning Based Optimization
TS	-	Transient Stability
TWB	-	Thin Well Beam
UPFC	-	Unified Power Flow Controller
UPQC	-	Unified Power Quality Conditioner
US	-	Under Shoot
USA	-	United States of America
VAR	-	Volt Ampere Reactive
VSC	-	Voltage Source Converter
WSCC	-	Western System Coordinating Council
WT	-	Wind Turbine
ZN	-	Ziegler Nichols
2DOF PID	-	Two Degree of Freedom Proportional Integral Differential

LIST OF SYMBOLS

C_p	-	Power Coefficient
$\mathrm{C}\tau$	-	Torque Coefficient
c1	-	Cognitive coefficient
c2	-	Social factor
Er	-	Random probability of Genetic Algorithm
$e(t)$	-	The error between nominal value and output value
$\vec{\mathrm{D}}_{\alpha}$	-	The distance of alpha wolf
$\vec{\mathrm{D}}_{\beta}$	-	The distance of beta wolves
$\vec{\mathrm{D}}_{\delta}$	-	The distance of delta wolves
dt	-	A small change in time t
$d\beta$	-	A small change in pitch angle
gbest	-	Swarm best solution
$\mathrm{I}^2\mathrm{R}$		Power loss in a conductor
J	-	Inertia moment of the Wind Turbine rotor
lb	-	Lower bound
K	-	Open-loop gain of Wind Turbine
K_i	-	The integral gain of the PID controller
K_p	-	A proportional gain of PID controller
M_p	-	Maximum overshoot
pbest	-	Personal best solution
Pc	-	Crossover probability of Genetic Algorithm
P_{eff}	-	Output energy efficiency index
Pm	-	Mutation probability of Genetic Algorithm
P_m	-	The mechanical power of the Wind Turbine
$P-Q$	-	Active power- reactive power
P_{sm}	-	Output power smoothing index
R	-	Rotor radius
T_e	-	Electromagnetic torque of a generator
T_m	-	Mechanical torque of Wind Turbine

T_β - The time constant of pitch actuator of Wind Turbine

$\vec{V}^{t}$ - The velocity of the particle at time t.

$\vec{V}^{t+1}$ - Update of particle velocity at time

w - Inertia weight

$\vec{X}$ - Position of prey

$\vec{X}_\alpha$ - Position of alpha Wolfs

$\vec{X}_\beta$ - Position of beta Wolfs

$\vec{X}_\delta$ - Position of delta Wolfs

$\vec{X}_1$ - Update Position of alpha Wolfs

$\vec{X}_2$ - Update Position of beta Wolfs

$\vec{X}_3$ - Update Position of delta Wolfs

$\vec{X}^{t}$ - Particle position at time t.

$\vec{X}^{t+1}$ - Particle update position at time t

pu - per unit

s - Laplace factor

tf - Transfer function

ub - Upper bound

α - Alpha

β - Pitch angle beta

δ - Delta

ϑ - Theta

ρ - Rho

π - pi

λ - Rotor tip speed ratio

ω - Rotor speed

ω_n - Natural frequency parameter of second-order Wind Turbine

ζ - Wind damping ratio zeta

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The world is facing environmental degradation such as green gas and radiation emissions, oil spills due to the widespread burning of fossil fuels [1] and nuclear radioactive materials to generate electricity. The high electricity demand [1] causes the depletion of fossil fuel reserves and their high costs [2] and these forced the stakeholders in the power industry to encourage the integration of Renewable Energy Sources (RES) in the power system [2]. The environmental degradation propelled the global campaign to reduce dependency on fossil fuels and focus on RES as the best electricity generation source, free from green gas emission for the sustainable environment [3, 4]. The campaign is encouraging the conduct of research for Hydro, Wind, Photovoltaic, Geothermal and Bio-energy sources to replace fossil fuels for generating electricity [4]. From another perspective, the disadvantages of constructing the long transmission system to supply power to remote communities in the traditional power system, such as the high cost of construction the long transmission lines with high copper losses, also are encouraging the integration of RES in the sub-transmission and the distribution networks, close to the load centres. Furthermore, the deregulation of the electricity market and the power industry is another factor pushing the integration of RES in the power system [5]. Moreover, the government incentives for using alternatives to fossil fuels encourage RES integration in the power system [6].

1.1.1 Stochastic Wind Turbine Outputs

Wind speed is a random process, and its cubic relationship with the Wind Turbines' aerodynamic power can causes instability in the wind power generation. Therefore, a power system with integrated Wind Turbines can experience instability due to the integration [7]. Besides the intermittent nature of the Wind Turbine outputs, the introduction of power electronic control devices in Wind Turbines; the vibration of the supporting frame of the Wind Turbine and blade shedding affects the power system's integrated power system with Wind Turbines. The vibration problems in the wind turbine system's supporting structure cause harmonics, while blade shedding cause flickers. The Wind Turbine output's intermittency causes stochastic reactive power consumption by Squirrel Cage Induction Generator, Doubly-Fed Induction Generator, and rotor wound Induction Generator [8]. The stochastic reactive power consumption of Induction Generators in the Wind Turbine creates voltage and frequency instability in the generator's outputs.

1.1.2 Solutions to the instability in the outputs of Wind Turbines

In the literature, different researchers proposed different methods of solving the fluctuations in the Wind Turbine outputs. Considering the Wind Turbine's aerodynamic power, the Radial Basis Neural network and PSO tuned collective pitch control were applied in [9] to reduce the Wind Turbine output fluctuations. In [10] the Intelligent Genetic Algorithm (IGA) tuned PID controller was implemented in the blade pitch control to reduce fluctuations in the Wind Turbine output. The Firefly Algorithm tuned pitch angle controller was applied in [11] to control the Wind Turbine's mechanical power. While in [12], the Wind Turbine's dynamic stability was enhanced using a metaheuristic optimizer tuned blade pitch controller.

1.2 Problem Statement

i. The ZN, GA and PSO tuning techniques applied by the Researchers for tuning the PI(D) controller in the pitch controls of Wind Turbines for power limitation and dynamic stability are the well-established methods in the literature, but they have the following limitations:

   a. The ZN tuned PID controller implemented in the pitch control of Wind Turbine in [13] does not produce the optimal control performance because the ZN tuning technique has high overshoot, oscillation and settling time.

   b. The PSO applied in [14], [15], [159] and [160] to tune the PID controller in the pitch control of Wind Turbines has inadequate convergence speed. Also, the PSO can be trapped into a local optimum as the best solution when solving complex problems like tuning the PI controller in the pitch control of the Wind Turbine.

   c. The GA is popular for PID controller tuning because of its accuracy and can solve tuning problems that are not well formulated. But it can be stuck in a local optimum.

ii. In the standard GWO the best positions of Alpha (λ), Beta (β) and Delta (δ) wolves are used to update the positions of the ω wolves have equal influences. The equal influences of Alpha (λ), Beta (β) and Delta (δ) wolves in updating the positions of ω wolves have violated the hierarchy class of the wolves which have the possibility not to provide optimal tuning results.

iii. The PSO, GA and ZN tuned PI controllers implemented in the pitch control of fixed speed Wind Turbines have the possibility of not providing optimal pitch control performance leading to low conversion of wind kinetic energy to aerodynamic power in the Wind Turbine because of the limitations in the PSO, GA and ZN tuning techniques mentioned in problem statement one.

iv. The PSO, GA and ZN tuned PI controllers implemented in the pitch control of SCIG and DFIG Wind Turbines have the possibility not providing optimal pitch control performance leading to dynamic instability in the aerodynamic power and torque of the Wind Turbines because of the limitations in the PSO, GA and ZN tuning techniques mentioned in problem statement one.

1.2.1 Motivations

The pitch control of the Wind Turbine is complex and nonlinear. A GWO is a suitable Algorithm for solving complex and nonlinear optimization problems [19] and it can provide an optimal solution to the PI controller tuning problem of pitch control. Mir Jalili, Seedily reported that the GWO has better search performance compare to Fast Evolutionary Programme (FEP), Gravitational Search Algorithm (GSA), Particle Swarm Optimization (PSO) and Differential Evolutionary (DE), because it is simple in principle, fast and accurate in searching [20]. Based on the good convergence characteristics of the GWO, it is proposed in this study to tune the PI controller in the pitch control of the Turbine driving the SCIG and DFIG Wind Turbines separately. This study proposed the GWO-based tuning method for PI controller in the pitch angle control of Wind Turbine as a better alternative to PSO, GA and Zeigler Nichols tuning techniques because of the following:

a. GWO has better convergence characteristics than PSO and GA [21] because of its exceptional ability to adapt the value of the optimization parameter “a” [22].

b. It can also avoid local optimum because it has a balanced exploration and exploitation ability [23].

c. Furthermore, it is simple [24], robust and applied to complex optimization tasks [25].

To further harness the application of SCIG Wind Turbine for wind power generation, this study considered the optimal tuning of the PI controller in pitch control of SCIG Wind Turbine. It is cheap in unit cost; simple in design and construction; brushless; robust; low cost of installation and fewer maintenance requirements [7], [26], [27] compared to variable speed Wind Turbines. Furthermore, it possessed better regulation in heat, good regulation in speed, small size and light in weight compared to DFIG and PMSG Wind Turbines [28].

1.3 Research Objectives

To find solutions to the research problems the following research objectives are set:

i. To develop the mathematical model for tuning the PI controller in the pitch control of Wind Turbine using the GWO, which overcome the slow convergence associated with PSO and trapping into local optimum associated with GA.

ii. To modify the GWO updating mechanism for faster convergence and tuning results of PI controller in the pitch control of the Wind Turbine.

iii. To reduce the aerodynamic power error in SCIG Wind Turbine operating under stochastic wind speed, through the GWO tuned PI controller's implementation in the Wind Turbine's pitch control connected to a 22.9kV double circuit distribution system.

iv. To enhance the dynamic stability of the aerodynamic power and torque of the SCIG Wind Turbines and DFIG Wind Turbines, through the GWO tuned PI controllers' implementation in the pitch controls the Wind Turbines connected to a WCSS 9 Bus 3 Machine test Feeder.

1.4 Scope of the Study

The following are the scope of the study:

i. This study is on enhancing the power efficiency of the SCIG Wind Turbine connected to the 22.9 kV distribution system by implementing a GWO tuned PI controller in the pitch control of the Wind Turbine. Also, it is on smoothing the SCIG Wind Turbine output by implementing a GWO tuned PI controller in the pitch control of the Wind Turbine. Furthermore, the study considered the GWO tuned controller’s implementation in the 8x3MW SCIG Wind Farm and the 8x3MW DFIG Wind Farms’ pitch control for dynamic stability enhancement in the Wind Turbines outputs. The SCIG Wind Turbine model considered in this study is specified in IEC 61400-27-1 standards for power system stability analysis [29].

ii. This study considered the PI controller's optimal tuning in pitch control of DFIG and SCIG Wind Turbines for aerodynamic power limitation and dynamic stability of their outputs.

iii. This study considered the small perturbation of rated wind speed, step-change in the generator’s nominal power in testing the impact of tuning the PI controller in pitch control on Wind Turbine outputs' dynamic stability.

iv. The impact of optimal tuning of PI controller in pitch control on the mechanical and electrical parameters of DFIG and SCIG Wind Turbines are studied.

v. This study is on the SCIG and DFIG Wind Turbines operation in region III of their power-speed characteristics.

vi. This study is on the PI controller's optimal tuning in pitch control of Wind Turbines at the mechanical subsystem of Turbines.

1.5 Significance of the Study

Presently the DFIG Wind Turbines are dominant in the Wind Turbine industry while the SCIG Wind Turbines dominated the same industry before the year 2000 [13], but they are still found in the Wind Farms [30] [31]. A brief survey of existing SCIG Wind Turbine installations is conducted to show the significance of conducting the PI controller’s optimal tuning in SCIG Wind Turbines’ pitch control. There are 105

Nordex N43-600 kW-three blades and 117 numbers of VESTAS 660kW stall regulation Wind Turbines located in Zafarana, Egypt [32]. Also, fixed-speed Wind Turbines are found in Nysted Offshore Wind Farm in Denmark. Moreover, the fixed-speed Wind Turbines contribute to a sizeable 20% of the Wind Energy Conversion Systems in Europe because of their simplicity in design and low maintenance cost [33] [34], [35]. The medium and the large scales fixed-speed Wind Turbines, both horizontal and vertical axes, are located in New York, on the coast of long island USA [36]. Table 1.13 shows some Wind Turbines with the Asynchronous generator concept found in the market [37]. There are different researches on the constant speed Asynchronous Wind Turbine concept are reported as in [38], [39], [40] and [41] et cetera. The power generation at the Wind Turbine outputs stochastic due to its cubic relationship with wind speed, and at high wind speed, the pitch angle control is applied to limit the output power to nominal power. In this study, the optimal tuning of Wind Turbines' pitch angle control is to enhance the pitch control performance. The significant of optimal tuning of pitch controls of the Wind Turbines are limit the output power to nominal power to reduced power error and output fluctuations and provide a better dynamic response at the Wind Turbine outputs.

Table 1.1 List of fixed speed Wind Turbines found in the market

S/N	**Speed control**	**Gear-box**	**Generator**	**Capacity**	**Manufacturer**	**Ref.**
1	Constant	Multistage	Asynchronous	1.5 MW 2.1 MW	Suzlon	[42]
2	Constant	Multistage	Asynchronous	2.3 MW 3.6 MW	Siemen wind	[43]
3	Constant	Multistage	Asynchronous	3.0 MW	Acciona	[30]
4	Constant	Multistage	Asynchronous	3.0 MW	Creative Wind Energy	[30]
5	Constant	Multistage	Asynchronous	3.0 MW	Guodian United Power	[31]
6	Constant	Multistate	Asynchronous	0.75 MW	Wind World	[44]
7	Constant	Multistage	Asynchronous	1.0 MW	Fuhrlande	[33]
8	Constant	Multistage	Asynchronous	2.5 MW	Nordex SE	[34]

S/N	Speed control	Gear-box	Generator	Capacity	Manufacturer	Ref.
9	Constant	Single-stage	Asynchronous	2.05 MW 2.5MW	Eviag	[45]
10	Constant	Multistage	Asynchronous	0.75 MW 0.90 MW	NEG Micon	[46]
11	Constant	Multistage	Asynchronous	0.10 MW 0.12 MW	Danish Wind Turbines ltd	[39]
12	Constant	Multistage	Asynchronous	0.30 MW	Nordtank	[40]
13	Constant	Multistage	Asynchronous	2.3 MW	Danish Wind Turbines ltd	[41]

The significance of the study is itemized as follows:

i. The implementation of GWO tuned PI controller in the pitch control of fixed speed SCIG Wind Turbine connected to a 22.9kV distribution system can reduce the mean power error at the output power of the SCIG Wind Turbine compared to PSO tuned PI controller, GA tuned controller, Fuzzy controller and Hybrid controller. The GWO tuned PI controller’s implementation in the SCIG Wind Turbine's pitch control has smoothed out the fluctuation in the Wind Turbine output compared with the output fluctuation provided by the PSO tuned PI controller, GA tuned controller, Fuzzy controller and Hybrid controller. Therefore, this study is significant because of the enhancement of the fixed speed SCIG Wind Turbine’s output power and reduction of fluctuation in its output which can increase the utilization of SCIG Wind Turbine in wind power generation.

ii. The study has enhanced the dynamic stability of the outputs of SCIG and DFIG Wind Turbines due to optimal tuning of pitch control of the Turbines using GWO. The enhancement in the dynamic stability in the pitch angle trajectory is significant because can lead to less stress on the pitch actuator which can increase its life span. Also, this can reduce maintenance costs of pitch actuators in Wind Turbines.

iii. The dynamically enhanced SCIG and DFIG Wind Turbine output due to the optimal tuning of PI-based pitch control using GWO and coupled to the distribution system can enhance the dynamic stability of the system.

1.6 Thesis Outline

This thesis contains five chapters. The introduction is Chapter One, where the research background was presented. It also includes the problem statements, research gap, motivation, research objectives, the study's scope, and the significance of the research and the thesis outline. Chapter two contains the Wind Turbine operation, classification of Wind Turbines, dynamic stability of Wind Turbine outputs, Wind Turbine output dynamic stability index, Wind Turbine pitch controls, and their classification. The previous works on the PID controller's optimal tuning based on optimizations for general applications were reviewed. Then the general approaches of tuning the PID controllers using GWO were presented. In the same Chapter Two, the GWO tuning of PID controllers in the control loops of power electronics converters for MPPT in the Wind Turbines and grid synchronization was reviewed. And finally, the previous works on the optimal tuning of PI(D) controllers in pitch controls of Wind Turbines were also reviewed.

Chapter three contains a two-stage research methodology. In the first stage, the proposed GWO-based tuning technique for PI controller in Wind Turbine's pitch control was described using a block diagram. The transfer function of the closed-loop pitch control of the Wind Turbine was formulated. And the Integral Time multiplied Square Error (ITSE) objection function for optimal tuning of the PI controller in Wind Turbine's pitch control was developed. The objective function is based on the power error between the generator's nominal power and the Turbine's aerodynamic power. The mathematical modelling of tuning the PI controller in the Wind Turbine's pitch control sequentially using the GWO, PSO and GA were presented in chapter three. The performance metrics for comparing the GWO, PSO and GA performances in tuning the PI controller in pitch control were provided. A description of how the best tuning results from the four search spaces were implemented in the PI controller in pitch control of the Wind Turbine is provided. Four case studies were conducted to validate the proposed GWO-based tuning method for PI controller in Wind Turbine's pitch control by comparing it with PSO, GA-based methods, and ZN tuning method.

In chapter three, the interconnected Wind Turbine and its component models were presented. Furthermore, the mathematical models of the wind turbine output energy efficiency and output power smoothing index line were presented. The results of the PI controller's optimal tuning in Wind Turbine’s pitch control based on GWO, PSO and GA for four search spaces were presented in chapter four. In the same chapter, the results of the implementation of selected tuning results of PI controller in the pitch control of the Wind Turbine for four case studies were presented. In the first case study, the SCIG Wind Turbine connected to a distribution line was tested with variable wind speed. The SCIG Wind Turbine operated in constant speed mode without reactive control at the generator’s stator terminals. In the second case study, the SCIG Wind Turbines in the Wind Farm connected to bus 2 of the WSCC 9 Bus 3 Machines test feeder were tested with unit-step above rated wind turbines’ wind speed. For the third case study, the DFIG Wind Turbines in a Wind Farm connected to WCSS 9 Bus 3 Machine test feeder was tested with consecutive unit-step above rated wind speed of the Wind Turbine. And for the fourth case study, the DFIG Wind Turbines located in the Wind Farm was connected to bus 2 of WSCC 9 Bus 3 Machine test feeder, were tested with a 10% decrease in the nominal power of their pitch controls. All the results from mechanical, electrical parameters of the Wind Turbines and the PCC’s electrical results were presented and discussed in chapter four. Finally, chapter five contains the research outcomes, contribution to knowledge and future works.

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LIST OF PUBLICATIONS

The papers published during the study:

A. Indexed Journal

1. H. Sule, A. S. Mokhtar, J.J. Bin Jamian, A. Khidrani. & R. M. Larik. "Optimal tuning of Proportional Integral controller for a fixed-speed wind turbine using Grey Wolf Optimizer". *International Journal of Electrical and Computer Engineering (IJECE),* Vol. 10, No. 5, 2020, pp. 5251~5261. ISSN:2088-8708, doi:10.11.59/ijece.v10i5. (**Indexed by SCOPUS**).

B. Indexed Conference Proceedings

1. A. H. Sule**,** A.S. Mokhtar, J.J. Bin Jamian, U. U. Sheikh & A. Khidrani, "Grey Wolf Optimizer Tuned PI Controller for Enhancing Output Parameters of Fixed Speed Wind Turbine". *In 2020 IEEE International Conference on Automatic Control and Intelligent Systems (12CACIS 2020),* pp 118-122, https://doi.org/10.1109/I2CACIS49202.2020.9140171 *(***Indexed by SCOPUS).**

2 A. H. Sule, A.S. Mokhtar, J. J. Bin Jamian & Z. A. Arfeen, "Optimal rotor blade control using Grey Wolf Optimizer for small signal stability of SCIG Wind Turbine". *IOP Conference Series: Material Science and Engineering*, 1051 (2021) 012035, pp 1-11, doi:10.1088/1757-899X/1051/1/012035 **(Indexed by SCOPUS)**