Design and implementation of optimal controller for DFIG-WT using autonomous groups particle swarm optimization

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ABSTRACT

There are many types of generators used within wind energy such as doubly fed induction generator (DFIG). Particle swarm optimization (PSO) algorithm is simple, robust and easy to implement. In addition to the privilege of PSO, autonomous groups particle swarm optimization (AGPSO) has the advantages of using diverse autonomous groups which result in more randomized and directed search. Applying AGPSO to tune PI controller to control DFIG is proposed in this paper. An implemented laboratory prototype consists of brushless DC motor (BLDC) for simulating the various wind speeds. Wound rotor induction machine, working as DFIG. This system is a stand-alone system. System identification strategy was introduced in this work. In this study, AGPSO is suggested for tuning the PI controller. Different case studies are performed, such as step changes in both speed and electrical load for showing the effectiveness of the proposed algorithm. For comparison PSO is used to tune the PI controller. Results from experiments clarify the feasibility of the proposed methodology. It is approved that AGPSO achieves the prevalent control execution (quicker transient response and more modest steady state error (ess)) contrasted with the PSO in tuning PI controller when applied to be used with off-grid systems.

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1. INTRODUCTION

Wind energy generation has turned out to be one of the rapidest and the most significant source of renewable energy in the world because of the huge expends of electricity needs. Now, the variable-speed wind turbine (VSWT) fitted with doubly fed induction generator (DFIG) has a growing attention due to its advantages [1]. DFIG is the most used generator in variable speed fixed frequency wind power systems. In this paper DFIG system is applied to stand-alone system. Different to grid-connected wind turbine (WT) systems, off-grid system should maintain active and reactive power beside matching the generation and load, regardless of variation in wind speed and load changes [2], [3].

Fulfilled transient performance can't be accomplished by customary PI control for the DFIG because of nonlinear control characteristics of DFIG. Subsequently this work delivers the issue to build up a smart control strategy for the DFIG for off-grid system. Various control techniques, for example, Appling adaptive, and fuzzy logic. The famous proportional-integral (PI) controller ,which is widely used in WT due to it is simple [4] and other studies found in [5]-[7]. However, it is not easy to get the required performance if its parameters isn’t tunned. Figure 1 shows the PI controller.

The parameter settings of the PI controller are the vital of the PI controller design because they directly affect the control performance of the system. Over the most recent couple of years, the heuristic algorithms are applied to fine-tune the PI controller. Numerous master's focus on the exploration of the intelligent algorithms, for example, the neural network and its mutation algorithm [8], [9]. The controller parameters or gains (Kp and Ki) are picked to meet recommended performance rules indicated as far as rise and settling times overshoot, and ess, following a step change in the demand [10].

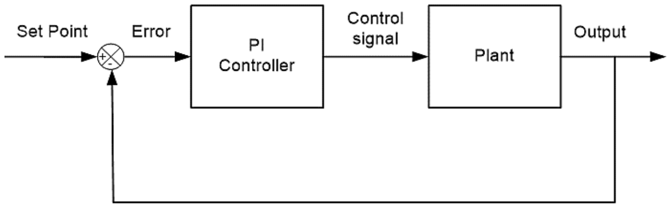


Figure 1. PI controller

Many researches were dedicated to the insightful PI controllers, for example, the fuzzy and variable gain algorithms [11], [12] however the fuzzy and variable gain rules actually should be optimized. Thus, the biological optimization algorithms such as the evolutionary computing, swarm intelligence, and so on, were introduced to improve the optimization of PI parameters [10], [13]-18]. Swarm intelligence has purposed PSO and autonomous groups PSO (AGPSO) that have opened paths to a new generation of advanced process control. These advanced techniques to design control systems are, in general, dependent on achieving optimum performance with various types of disturbance that are unknown in most practical applications [15]-[19].

In this paper, the system modeling is described in section 2. Also, in section 2 validation of the identified model. In section 3 explanation of applying the optimization techniques is presented. While the results and discussions are presented in section 4. Finally, the conclusion is given in section 5.

2. SYSTEM MODELING

2.1. Implemented wind turbine and DFIG system

A system consists of DFIG, brushless DC motor (BLDC), Drive circuit, inverter, speed measuring unit, reactive power measuring unit and data acquisition card shown in Figure 2. Optimization techniques is applied to PI controller in MATLAB/Simulink while connecting the data acquisition card to the MATLAB/SIMULINKusing Data Acquisition Toolbox. and the block diagram describing the system shown in Figure 3. The technical data of the system is as in [4].

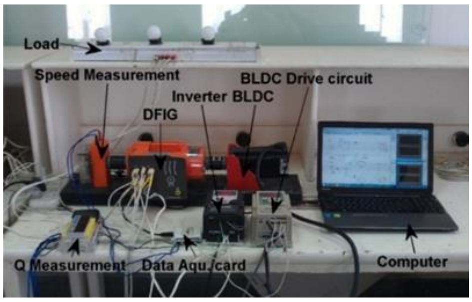


Figure 2. General view of the system setup

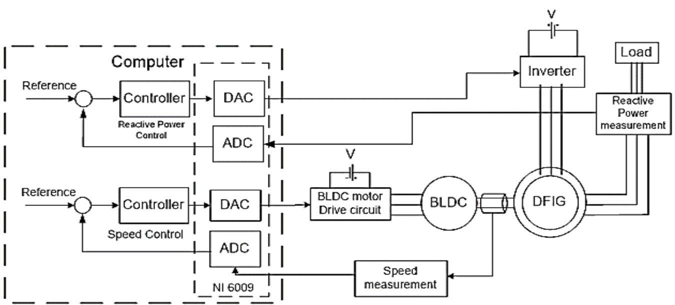


Figure 3. Block diagram of DFIG system test bench

2.2. Lab wind turbine system

MATLAB system identification toolbox is utilized to obtain the transfer function (TF) of DFIG for VAR control and BLDC for speed control [20], [21]. The TF of the VAR loop of DFIG is as in (1) while The TF of the speed loop of BLDC is as in (2) with matching of the real system with about 92% for the VAR TF and about 95% for the Speed TF. Figure 4 and Figure 5 how the output measured and the percentage fit of each simulated model to the output measured for VAR loop and speed loop respectively.

$$G_Q(S) = \frac{8134\ S^2 + 2.101e04\ S + 411.6}{S^4 + 26.4\ S^3 + 215.5\ S^2 + 508.4\ S + 7.229} \quad (1)$$

$$G_{Speed}(S) = \frac{1279\ S^2 + 5.867e05\ S - 1.053e04}{S^3 + 50.21\ S^2 + 915\ S + 2.506e-12} \quad (2)$$

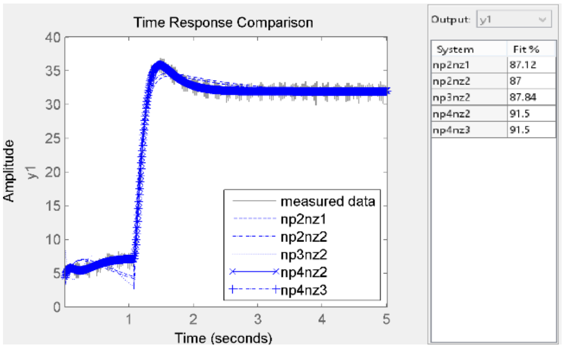


Figure 4. Measured and simulated TF model output of VAR loop

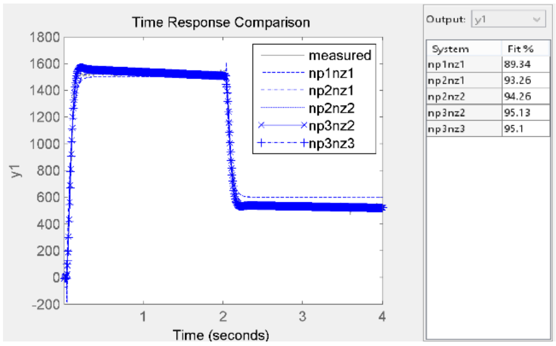


Figure 5. Measured and simulated TF model output of speed loop

2.3. Validation of the implemented models

Figure 6 shows the validation of identified models for implemented system for step input. It can be seen from Figure 6 that the matching of the identified model with the implemented one. Figure 7 shows the PI controller with tuning algorithm.

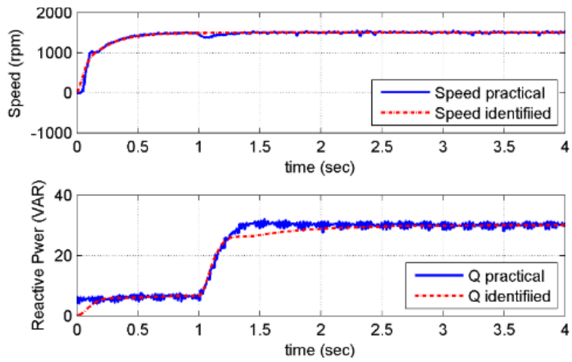


Figure 6. VAR and speed response of practical and identified model

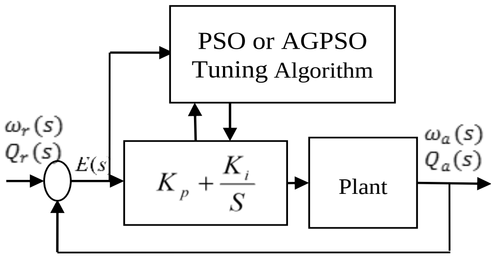


Figure 7. Structure of system with PI tuning algorithms

3. METHOD

3.1. Objective function

The PI controller has normally a TF given by (3) [21]:

$$G_c(s) = K_p + \frac{K_i}{s} \quad (3)$$

where, Kp, and Ki indicates the proportional, and integral gains respectively. In this paper, PSO, and AGPSO algorithms are used to optimize the the controller parameters for VAR loop and speed control based on performance index. The performance index are weighted goal attainment Method 1,2 (WGAM1), and (WGAM2), declared by (4), and (5) [21].

$$WGAM1 = \frac{1}{[c_1(t_r - t_{rd})^2 + c_2(M_p - M_{pd})^2 + c_3(t_s - t_{sd})^2 + c_4(e_{ss} - e_{ssd})^2]} \quad (4)$$

$$WGAM2 = \frac{1}{(1-e^{-\beta})\cdot(M_p+e_{ss})+(e^{-\beta})\cdot(t_s-t_r)} \quad (5)$$

Where, r(t): required output, y(t): plant output, e(t): error signal, β: weighting factor, c_1 to c_4: weighting factors, trd, Mpd: desired rise time, and maximum overshoot. tsd, and essd: desired settling time, and steady state error. In (4) the actual parameters (tr, Mp, ts, and ess) are used to find the best solution for the objective function by $\sum(errors)^2$ of actual and desired parameters (trd, Mpd, tsd, and essd). In (5), The factor β is above 0.7 to minimize Mp and ess. meanwhile β is below 0.7 to minimize tr and ts [4].

3.2. Optimization techniques

Two techniques have been used in this paper PSO as a basic technique and AGPSO as a modern one. In the PSO algorithm, each particle velocity is adjusted according to its experience and the other particles experience as in [17]-[19]:

$$v_i^{k+1} = wv_i^k + c_1 rand_{1i}(pbest_i - s_i^k) + c_2 rand_{2i}(gbest - s_i^k) \quad (6)$$

where, v_i^k is the present velocity of particle i at iteration k, v_i^{k+1} is the updated velocity of particle i, w is the inertia weight, c1, c2 are two acceleration positive PSO constants, s_i^k is the present position of particle i at iteration k, rand1i, rand2i are random numbers between 0 and 1, pbesti is the best position of particle i, and gbest is the global best position of the group so far. The new position s_i^{k+1} can be modified using the present position s_i^k and updated velocity v_i^{k+1}.

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (7)$$

The positive constants c1 and c2 are usually set between 0.5 to 2 [14].The inertia weight w is set as a decreasing linear function with the iteration number from 0.9 to 0.4 [22]-[24]. PSO parameters are summarized in Table 1.

In addition to the privilege of PSO, autonomous groups particle swarm optimization (AGPSO) has the advantages of using diverse autonomous groups which result in more randomized and directed search. Applying AGPSO to tune PI controller to control DFIG is proposed beside PSO. A mathematical model of the AGPSO is utilize different strategies for updating c1 and c2 [25]. Finding a good balance between c1 and c2 and considering them as dynamic coefficients. The dynamic coefficients of AGPSO algorithm are presented in the Figure 8 [25].

In Table 2, T indicates the maximum number of iterations and t is the present iteration. For instance, the particles of AGPSO utilizes two principal third root, two cubic functions for groups 1 and 2 in addition to one principal third root and cubic functions for groups 3 and 4.

Table 1. PSO parameters

Parameter	Value
Population size	10
Number of generations	10
Acceleration Constant c_1	0.5
Acceleration Constantc_2	1.5
Initial inertia weight w_{max}	0.9
Final inertia weight w_{min}	0.2

Table 2. Updating strategies

Algorithm	Updating formula C1	Updating formula C2
AGPSO		
Group1	$1.95-2t^{1/3}/T^{1/3}$	$2t^{1/3}/T^{1/3}+0.05$
Group2	$(-2t^3/T^3)+2.5$	$(2t^3/T^3)+0.5$
Group3	$1.95-2t^{1/3}/T^{1/3}$	$(2t^3/T^3)+0.5$
Group4	$(-2t^3/T^3)+2.5$	$2t^{1/3}/T^{1/3}+0.05$

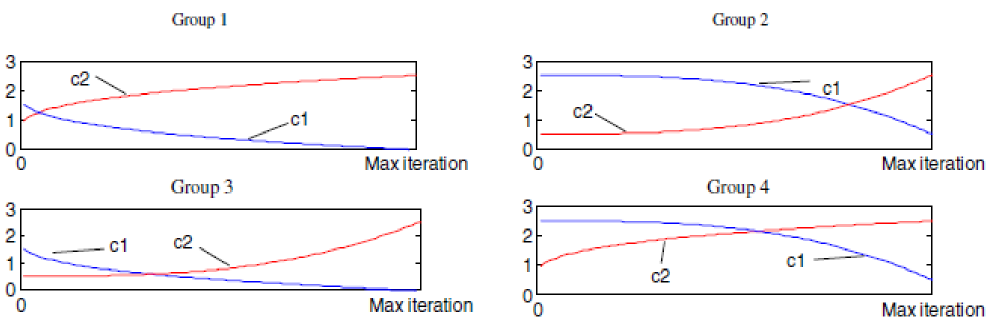


Figure 8. Mathematical models of autonomous groups for AGPSO [25]

4. RESULTS AND DISCUSSION
4.1. Simulation results of the identified system
4.1.1. Comparison between the proposed optimization techniques

For comparison purposes, the optimum PI parameters are searched for the TF of the identified models obtained by in (1) and (2). The results of the identified model by PSO and AGPSO controllers are shown in Table 3 and Table 4. The corresponding values of PI parameters are shown in Table 5 and Table 6. Also, the time responses are shown in Figure 9 and Figure 10.

It is concluded from the above comparison that the AGPSO has been proven to be more efficient than the PSO algorithm in seeking for the global optimum PI parameters with respect to the desired performance indices. Thus, the system performs better time response with the optimum PI controller.

Table 3. Results of the PSO, and AGPSO for PI controllers in simulation of VAR loop

Response	Optimization methods	Performance Criteria	
		WGAM1	WGAM2
Value of fitness function	PSO	1.5392	1.4392
	AGPSO	0.2538	0.7209
Rising time(sec)	PSO	0.087399	1.4055
	AGPSO	0.3709	0.1735
Overshoot percentage	PSO	0	0
	AGPSO	0.0079	0.0044
Settling time (sec)	PSO	2.9721	2.9962
	AGPSO	1.505	0.9698
Steady state error	PSO	0.001282	0.00201
	AGPSO	0.0016	7.30E-04

Table 4. Results of the PSO and AGPSO for PI controllers in simulation of speed loop

Response	Optimization methods	Performance Criteria	
		WGAM1	WGAM2
Value of fitness function	PSO	0.11515	0.86391
	AGPSO	8.79E-04	0.1568
Rising time(sec)	PSO	0.60787	0.58724
	AGPSO	0.2787	0.1917
Overshoot percentage	PSO	0.046845	0.01337
	AGPSO	0.0253	0.0284
Settling time (sec)	PSO	1.103	1.5402
	AGPSO	0.5491	0.3617
Steady state error	PSO	-0.00578	-0.00357
	AGPSO	-0.0025	-0.0025

Table 5. Parameters of PI controllers for VAR loop

PI Gains	Optimization methods	Performance Criteria	
		WGAM1	WGAM2
Kp	PSO	0.061582	0.027787
	AGPSO	0	0.0196
Ki	PSO	0.076026	0.054485
	AGPSO	0.0716	0.1554

Table 6. Parameters of PI controllers for speed loop

PI Gains	Optimization methods	Performance Criteria	
		WGAM1	WGAM2
Kp	PSO	0.000296	0.003862
	AGPSO	9.50E-04	3.06E-04
Ki	PSO	0.005508	0.008898
	AGPSO	0.0130	0.0130

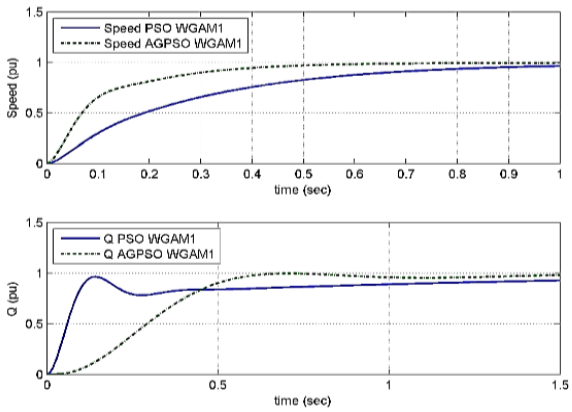


Figure 9. Simulation with respect to WGAM1

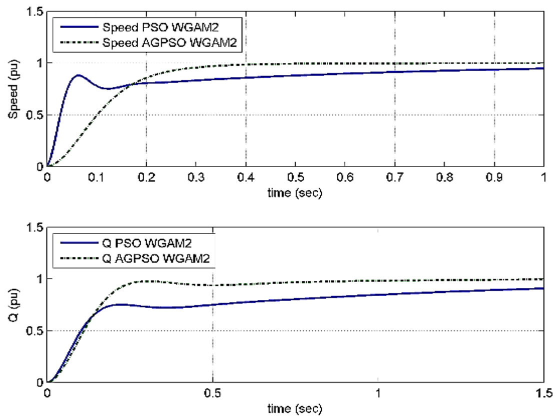


Figure 10. Simulation with respect to WGAM2

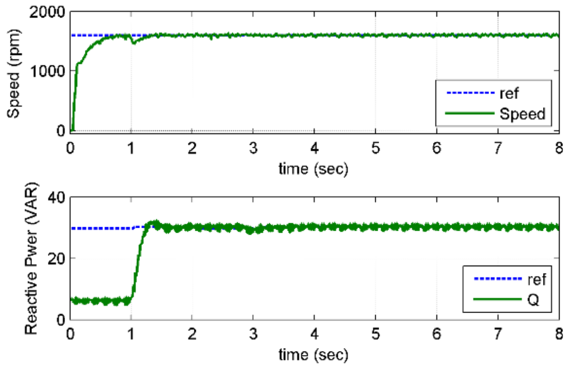
4.2. Implementation results

To implement the proposed algorithm performance for controlling the system, four cases are simulated:

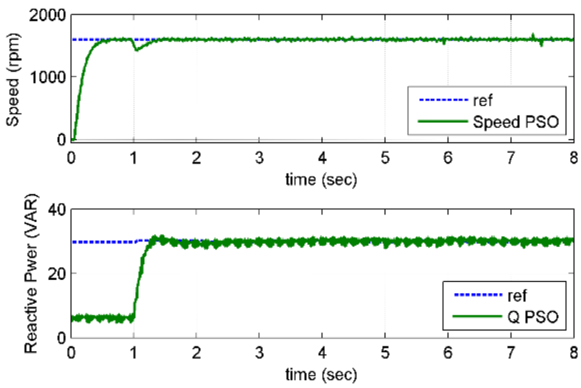
Case 1: 3-phase RL load, 1600 rpm, and 30 VAR.
Case 2: 3-phase induction motor, 1600 rpm, and 30 VAR.
Case 3: 3-phase RL load, 1600 to 1400 rpm, and 30 VAR.
Case 4: 3-phase induction motor, 1600 to 1400 rpm, and 30 VAR.

In the experimentation, the resulted gains are Kp=0.0007 and Ki=0.01 for the speed regulation and Kp=0.02 and Ki=0.1 for the VAR regulation. The experimental results of the implemented system under the effect of PI, PSO-PI, and AGPSO-PI controllers are shown in Figures 11 to 14. Figure 11 shows the response of speed loop and corresponding response of VAR loop for case 1 (RL load, 1600 rpm, and 30 VAR) (a) PI controller, (b) PSO-PI controller, and (c) AGPSO-PI controller.

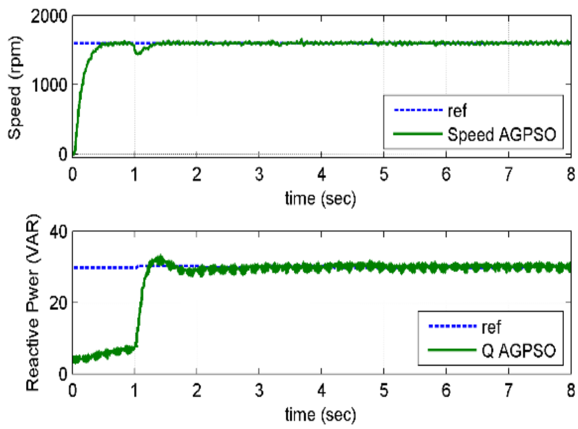
Also Figure 12, 13, and 14 show that responses for case 2 (induction motor, 1600 rpm, and 30 VAR), case 3 (RL load, 1600 to 1400 rpm, and 30 VAR), and case 4 (induction motor, 1600 to 1400 rpm, and 30 VAR) respectively. The Figures show the superior of AGPSO algorithm than PSO algorithm in finding the global optimum PI parameters and better time response.



(a)

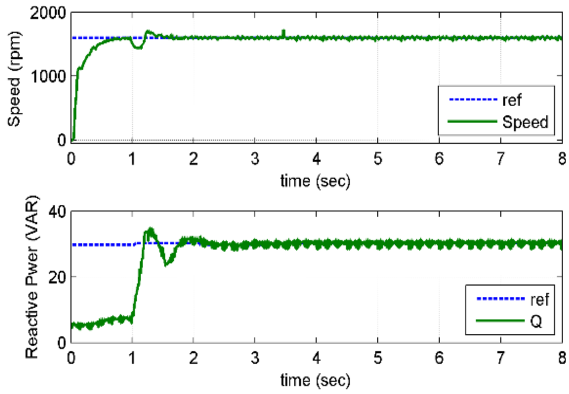


(b)

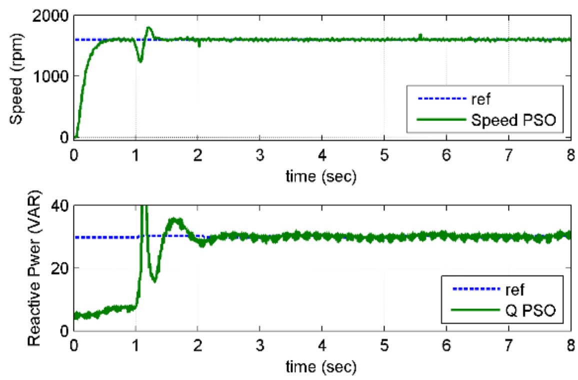


(c)

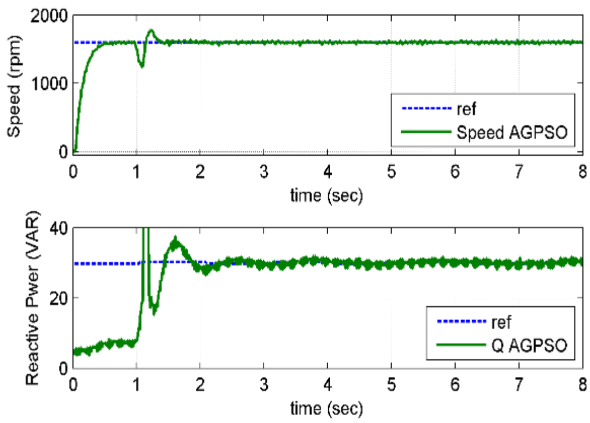
Figure 11. Experimental results of speed and VAR Case 1 at 1600 rpm: (a) PI controller, (b) PSO-PI controller, and (c) AGPSO-PI controller



(a)



(b)



(c)

Figure 12. Experimental results of speed and VAR Case 2 at 1600 rpm: (a) PI controller, (b) PSO-PI controller, and (c) AGPSO-PI controller

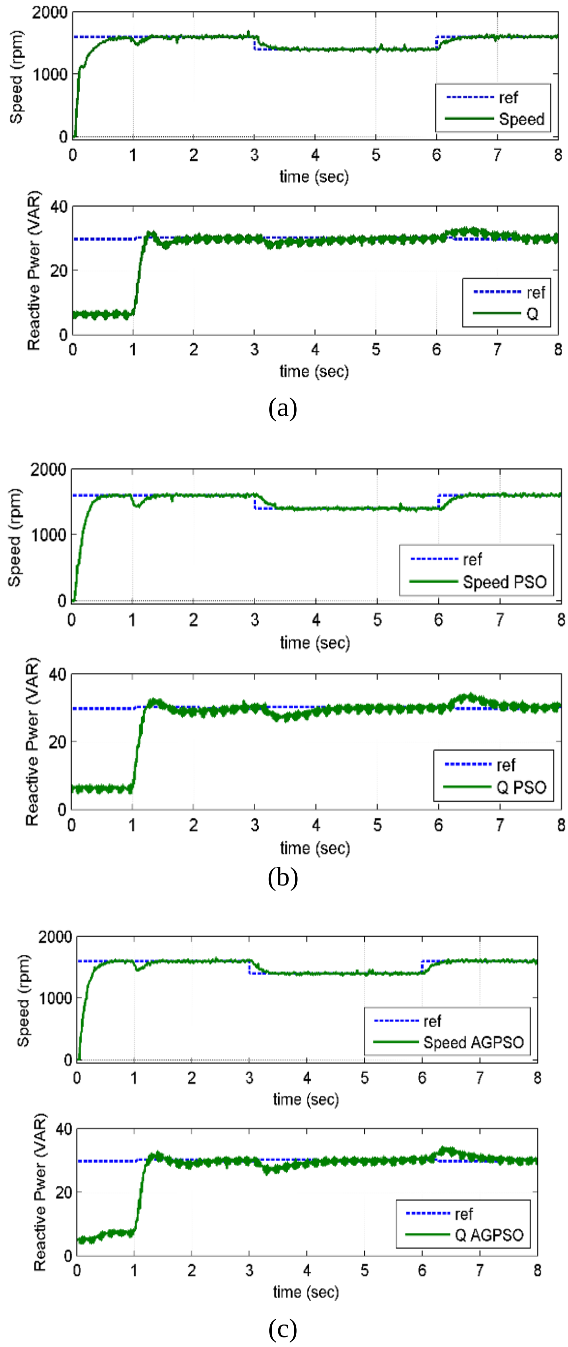


Figure 1. Experimental results of Speed and VAR Case 3 at 1600 rpm to 1400 rpm to 1600 rpm. (a) PI controller, (b) PSO-PI controller, and (c) AGPSO-PI controller

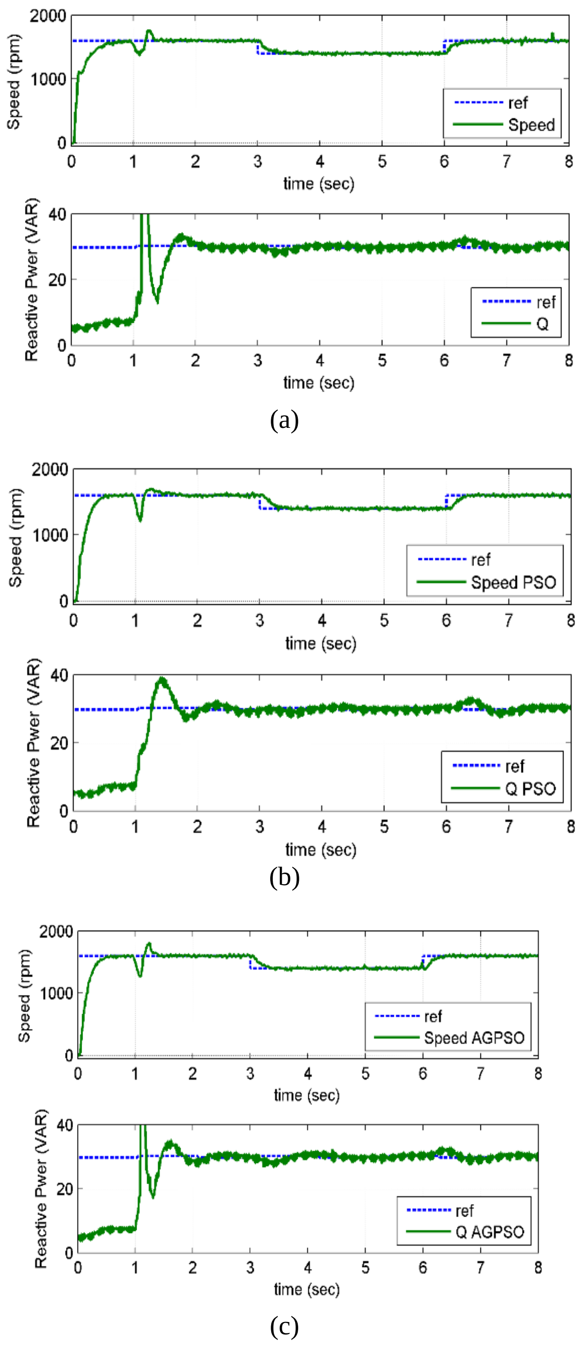


Figure 2. Experimental results of Speed and VAR Case 4 at 1600 rpm to 1400 rpm to 1600 rpm (a) PI controller, (b) PSO-PI controller, and (c) AGPSO-PI controller

5. CONCLUSION

This paper introduces a design and implementation of Optimal PI Controller for Test bed of DFIG driven by wind turbine using autonomous group PSO. Two optimization techniques PSO and AGPSO for PI controllers tuning of VAR loop beside speed loop of a DFIG driven by BLDC motor has been proposed in this work. The controllers were simulated in MATLAB/Simulink and then verified experimentally. System identification is also proposed to determine the VAR loop TF and and speed loop TF of the implemented system. The validation of identification shows the matching of the identified model with the implemented one. Results from experiments clarify the feasibility of the proposed methodology. It is approved that AGPSO achieves the prevalent control execution (quicker transient response and more modest steady state error (ess)) contrasted with the PSO in tuning PI controller. Experimental results show the superior of the AGPSO than PSO in optimizing PI parameters wrt the desired performance indices.

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