PID Design Using Particle Swarm Optimization and Iterative Linear Matrix Inequality for a Wind Power Plant

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Abstract – **This paper presents a Proportional-Integral-Derivative (PID) design using two techniques, namely, Particle Swarm Optimization (PIDPSO) and Iterative Linear Matrix Inequalities (PIDILMI), as applied to a multivariable blade pitch control for a wind turbine generating system comprising a synchronous generator connected to a large power system. The PID is used to control the electrical torque delivered to the power system. To show the effectiveness of the proposed techniques, divers tests, namely, step/tracking in the controlled variable, and variation in system parameters, are applied.**

I. INTRODUCTION

Wind energy, a form of renewable source, uses wind turbine to convert the energy contained in flowing air into electricity. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and presumed infinite availability of the prime mover that is converted into electricity [1-4]. Unfortunately, the contribution of wind power is still limited and covers only a small part of the total power system load. The rest is still fulfilled by conventional plants such as thermal, nuclear and hydro power plants. Therefore, the former hardly contributes in voltage and frequency control. Thus, frequency and voltage are controlled by large power plants usually of conventional types. Besides, if a disturbance occurs, the wind turbines are disconnected and reconnected when normal operation has been resumed. The tendency to increase their size will have more influence on overall power system behavior. Thus, their behavior in an electrical power system and interaction with other generating equipments and loads should be looked upon.

A wind turbine is essentially a machine that converts the kinetic energy of the moving air (wind) first into mechanical energy at the turbine shaft and then into electrical energy. The force of the wind creates aerodynamic lift and drag forces on the rotor blades, which, in turn, produce the torque on the wind turbine rotorAll wind turbines are therefore designed with some sort of power control. For the wind turbines, generated power is dependent on the wind speed. However, for large generators, rotor speed changes are quite smooth.

Previous work [5-9] has explored system performance with divers control techniques. In this work, PID setting gains are designed using two techniques. The first uses Particle Swarm Optimization (PSO) [10-13] as an optimization technique for an index representing the error between the reference and actual controlled values. In the second, Iterative Linear Matrix Inequalities (ILMI) technique is used [14-19]. The PID designed using the first controller is named PIDPSO whereas the second is named PIDILMI. In both cases, the PID controller is used to control the electrical torque delivered from a wind turbine generating system comprising a synchronous generator connected to a large power system. The effectiveness of the proposed techniques are demonstrated using divers tests, namely, step/tracking in the controlled variable, variation in system parameters, and gust effect, are carried out. Matlab platform with its control and LMI toolboxes [13,17] are extensively exploited.

I. SYSTEM MODELING

The wind turbine converts the kinetic energy of the moving air (wind) first into mechanical energy at the turbine shaft and then into electrical energy as depicted in Figure 1.

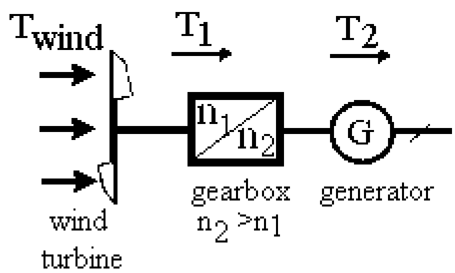


Figure 1. Block diagram of the wind turbine

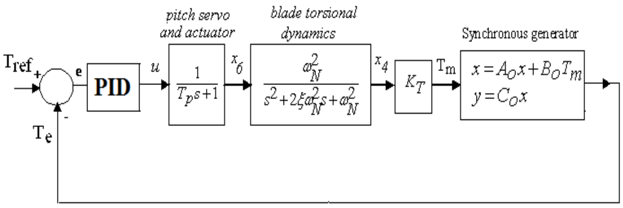


Figure 2. Wind turbine model for the system under study

The block diagram of the system under study is shown in Fig. 2 and the data are given in the appendix.

A. State-space representation

The variables shown in Fig. 2 represent small displacements around a selected operating point. The open-loop system can be written as

$$\dot{x} = Ax + B_1 u + B_2 v_g$$
$$y = Cx = T_e$$
$$u = K_P e + K_I \int edt + K_D \frac{de}{dt} \qquad (1)$$
$$e = T_{ref} - T_e$$

Where

$$x = \begin{bmatrix} \delta & \omega & e'_q & T_d & x_5 & x_6 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{\omega_o k_1}{2h} & 0 & -\frac{\omega_o k_2}{2h} & \frac{\omega_o k_{th}}{2h} & 0 & 0 \\ -\frac{k_4}{\tau'_{do}} & 0 & -\frac{1}{\tau'_{do} k_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -\omega_n^2 & -2\xi\omega_n^2 & \omega_n^2 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{\tau_p} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{1}{\tau_p} \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 & \frac{\omega_0}{2h} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} k_1 & 0 & k_2 & 0 & 0 & 0 \end{bmatrix}$$

And

u	control input
v_g	wind speed or gust

I. ITERATIVE LMI PID CONTROLLER

In Fig. 3, a transformation of the PID controller to a Static Output Feedback (SOF) controller is performed [18,20]. Consider the linear time-invariant system given by (1) and rewritten as follows:

$$\dot{x} = Ax + Bu, \quad y = Cx \qquad (2)$$

With $B=B_1$ and

$$u = F_1 y + F_2 \int_0^t ydt + F_3 \frac{dy}{dt} \qquad (3)$$

Where

x	state variable
u	control input
y	output
A, *B* and *C*	constant matrices
F_1, F_2, F_3	matrices to be designed.

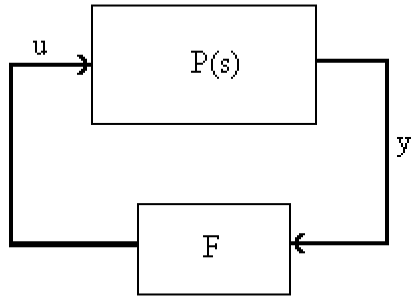


Figure 3 Multivariable PID

Let $z_1 = x$ and $z_2 = \int_0^t ydt$. Denote $z = [z_1^T z_2^T]$. The variable z can be viewed as the state vector of a new system whose dynamics are governed by

$$\dot{z}_1 = \dot{x} = Az_1 + Bu$$
$$\dot{z}_2 = y = Cz_1 \qquad (4)$$

i.e.

$$\dot{z} = \bar{A}z + \bar{B}u \qquad (5)$$

where

$$\bar{A} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix}$$

$$\bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

Combining (2) and (5) yields

$$y = Cz_1 = \begin{bmatrix} C & 0 \end{bmatrix} z$$

$$\int_0^t ydt = z_2 = \begin{bmatrix} 0 & I \end{bmatrix} z$$

$$\frac{dy}{dt} = C\dot{x} = CAx + CBu = \begin{bmatrix} CA & 0 \end{bmatrix} z + CBu$$

Let

$$\overline{C}_1 = \begin{bmatrix} C & 0 \end{bmatrix}$$
$$\overline{C}_2 = \begin{bmatrix} 0 & I \end{bmatrix}$$
$$\overline{C}_3 = \begin{bmatrix} CA & 0 \end{bmatrix}$$

And

$$\overline{y}_i = \overline{C}_i z, i = 1,2,3$$

Thus (3) becomes

$$u = F_1\overline{y}_1 + F_2\overline{y}_2 + F_3\overline{y}_3 + F_3CBu$$

Suppose $(I - F_3CB)$ is invertible, then

$$u = \overline{F}_1\overline{y}_1 + \overline{F}_2\overline{y}_2 + \overline{F}_3\overline{y}_3 \qquad (6)$$

Where

$$\overline{y} = \begin{bmatrix} \overline{y}_1^T & \overline{y}_2^T & \overline{y}_3^T \end{bmatrix}^T$$
$$\overline{F} = \begin{bmatrix} \overline{F}_1 & \overline{F}_2 & \overline{F}_3 \end{bmatrix}$$
$$\overline{C} = \begin{bmatrix} \overline{C}_1^T & \overline{C}_2^T & \overline{C}_3^T \end{bmatrix}^T$$
$$\overline{F}_1 = (I - F_3CB)^{-1} F_1$$
$$\overline{F}_2 = (I - F_3CB)^{-1} F_2$$
$$\overline{F}_3 = (I - F_3CB)^{-1} F_3$$

The problem of PID controller design reduces to that of a Static Output Feedback (SOF) controller design for the following system:

$$\dot{z} = \overline{A}z + \overline{B}u$$
$$\overline{y} = \overline{C}z \qquad (7)$$
$$u = \overline{F}\overline{y}$$

Once $\overline{F} = \begin{bmatrix} \overline{F}_1 & \overline{F}_2 & \overline{F}_3 \end{bmatrix}$ is found, the original PID gains can be recovered from

$$F_3 = \overline{F}_3(I + CB\overline{F}_3)^{-1}$$
$$F_2 = (I - F_3CB)\overline{F}_2$$
$$F_1 = (I - F_3CB)\overline{F}_1$$

The Iterative Linear Matrix Inequalities (ILMI) algorithm for Static Output Feedback (SOF) systems can be found in [19,20]:

II. SIMULATION RESULTS

To demonstrate the effectiveness of the proposed controllers, several tests are carried out and the results are presented for the wind power plant, described earlier, being driven by each of the proposed controllers. The simulation results are obtained using MATLAB package, control and LMI Toolboxes.

A. System with PIDPSO

The evolution of the cost function:

$$J = \sum_{t=0}^{t=2} \left[t^* \mid T_{ref} - T_e(t) \mid +10 * \omega(t) \right] \qquad (8)$$

is shown in Fig. 5. The system is subjected to 10% increase in the reference torque T_{ref}.

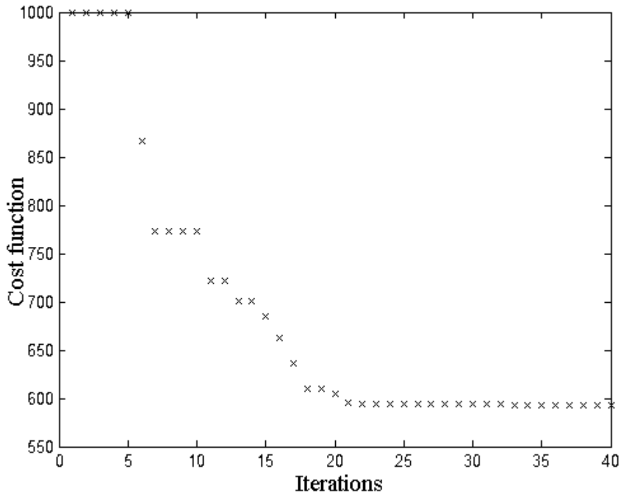


Figure 5 Cost function evolution

The linearized closed-loop state-space system with for PIDPSO is:

$a21= -\omega_o*k_1/(2*h)$	$a23= -\omega_o*k_2/(2*h)$
$a24= +\omega_o*k_{th}/(2*h)$	$a31= -k_4/ \tau_{do}'$
$a33= -1/(\tau_{do}'*k_3)$	$a54= -\omega_n^2$
$a55= -2*\zeta*\omega_n$	$a56= +\omega_n^2$
$a61=-(K_P*k_1+K_D*k_2*a31)/ \tau_p$	$a62=- K_D*k_1/ \tau_p$
$a63=-(KP*k2+KD*k2*a33)/ \tau_p$	
$a66= -1/ \tau_p$	$a67= +1/ \tau_p$
$a71= -K_I*k_1$	$a73= -K_I*k_2$
$b21= \omega_o/(2*h)$	$b22= \omega_o/(2*h)$
$b62=K_P/\tau_p$	$b63= K_D/ \tau_p$
$b72= K_I$	

```
Acl = [ 0     1      0       0       0       0       0
        a21  0     a23    a24    0       0       0
         a31  0      a33    0       0       0       0
         0     0      0       0       1       0       0
         0     0      0       a54    a55   a56    0
         a61  a62  a63    0       0       a66    a67
        a71   0     a73    0       0       0       0     ]

Bcl = [ 0     0      0
         b21 0      0
         0     0      0
         0     0      0
         0     0      0
         0     b62   b63
         0     b72   0      ]
```

PSO data are:

- iterations = 2
- inertia = 1
- correction factor = 2

A set of random numbers for Kp, K_I, K_D are generated in [0.01-2], [0.01-1], and [0.01-1] intervals, respectively.

The system closed-loop eigenvalues for PIDPSO are shown in Table 1 while the controller gains are given in Table 2.

B. System with PIDILMI

ILMI data are:

The positive definite starting matrix : Q=10

The obtained value of α is: α_{opt} = -5.4091 new

The system closed-loop eigenvalues for PIDILMI are shown in Table 1 while the controller gains are given in Table 2.

TABLE 1.

CLOSED-LOOP EIGENVALUES FOR THE SYSTEM WITH EACH OF THE PROPOSED CONTROLLERS

Eigenvalues	
PIDPSO	PIDILMI
-373.17	-0.98516 ± 91.158i
-34.516	-6.8155 ± 40.503i
-3.6113 ± 10.669i	-7.2102
-2.7672 ± 3.505i	-3.6468
-2.7246	-0.7099

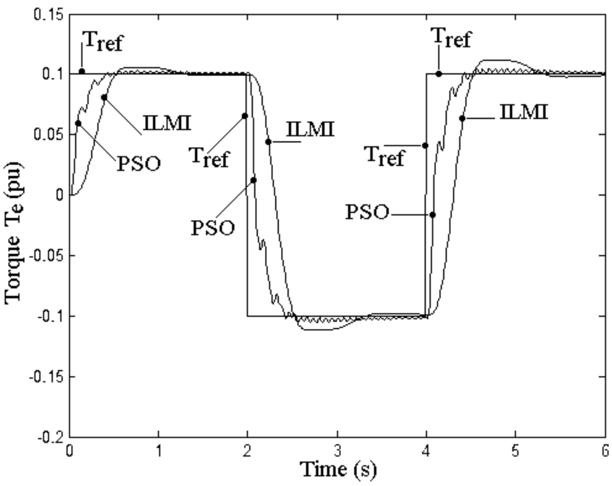
TABLE 2.

CLOSED-LOOP PID GAINS FOR THE SYSTEM WITH EACH OF THE PROPOSED CONTROLLERS

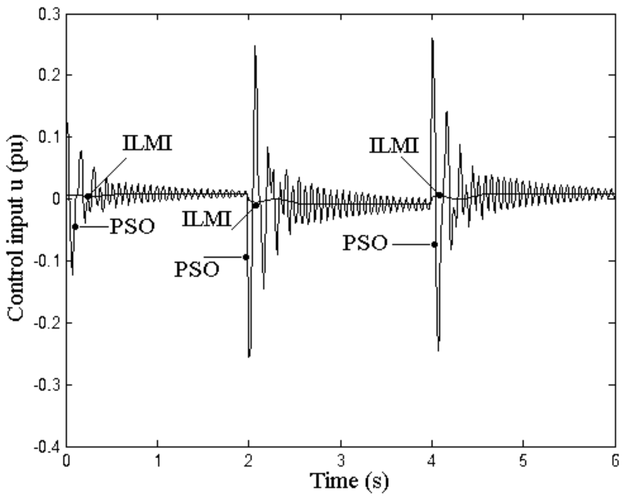
PID Feedback gains	
PSO	ILMI
0.052205	1.298
0.30318	0.1719
0.019398	0.89351

***Test 1*: Tracking-response**

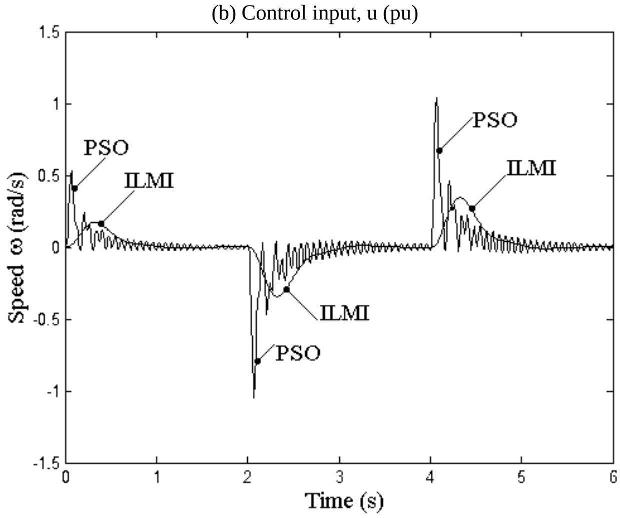
To test the effectiveness of the system to tracking the reference value of the torque, the system is subjected to a variation in T_{ref} as shown in Fig. 6 (a). The system response for the electromagnetic torque T_e, control input u, generator speed ω, and power angle δ are shown in Fig. 6. The system, equipped with the proposed controllers, is subjected to an increase by 10% then a decrease by 10% in T_{ref}. PIDILMI shows smooth response as compared to an oscillatory response but with relatively larger overshoots exhibited by PIDPSO with heavy oscillations.



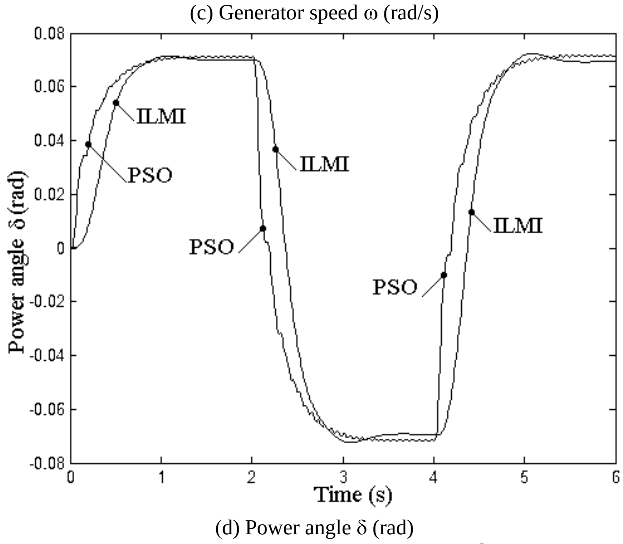
(a) Electromagnetic torque, T_e (pu)



(b) Control input, u (pu)



(c) Generator speed ω (rad/s)

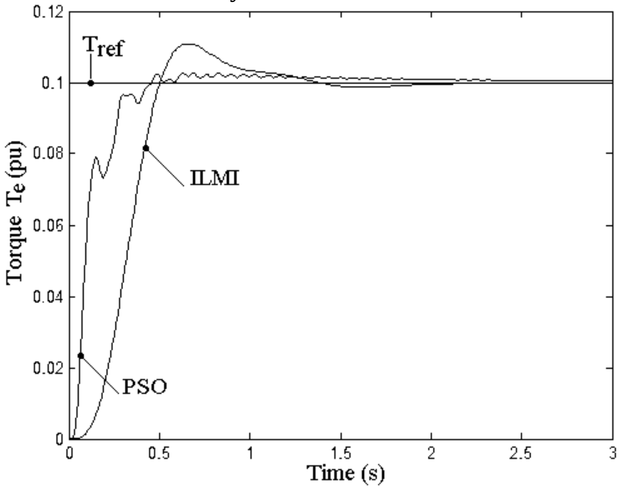


(d) Power angle δ (rad)

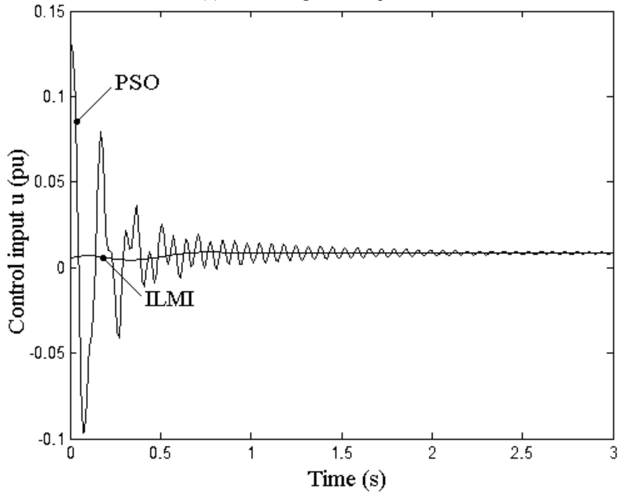
Figure 6. Step-response following T_{ref}=+5% the -5%

***Test 2*:** *Parameters Variation*

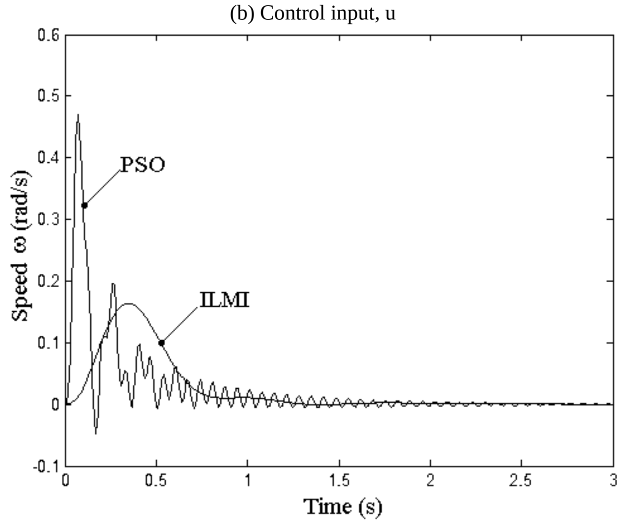
To test the robustness to parameters change, a 50% increase in the field transient time constant τ_{do}', 20% increase in the inertia constant h, and 20% increase in the armature resistance r_a. Fig. 7 shows the system response following a change in T_{ref} by +10% while experiencing the described parameters change. It is worth noting that the PID gains used are those found with nominal system parameters. It is clear that the system responds smoothly with ILMI but slower than PSO where pronounced oscillations are clearly shown.



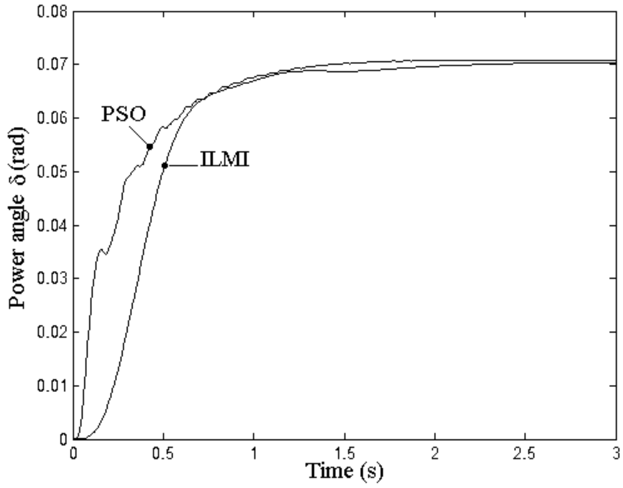
(a) Electromagnetic torque, T_e



(b) Control input, u



(c) Generator speed ω

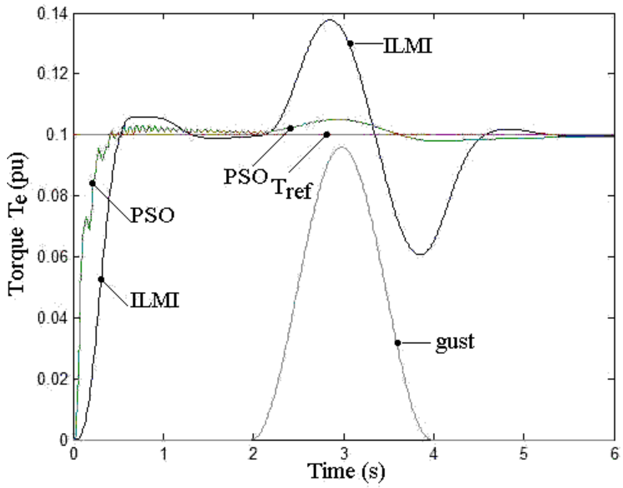


(d) Power angle δ

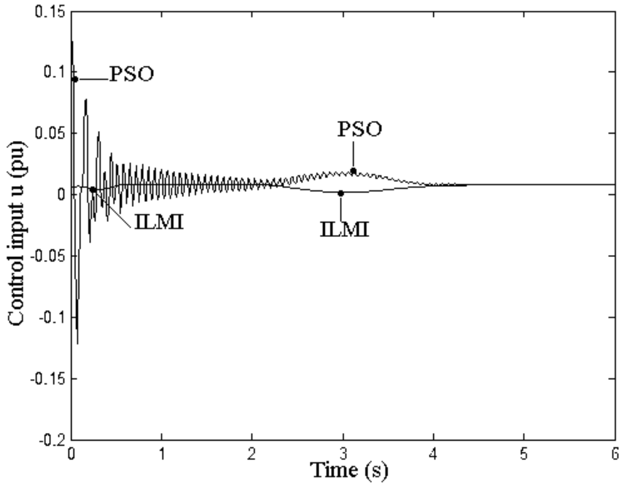
Figure 7. Parameters (τ_{do}', h, r_a) variation

***Test 3**: Wind Speed Variation (Gust) effect*

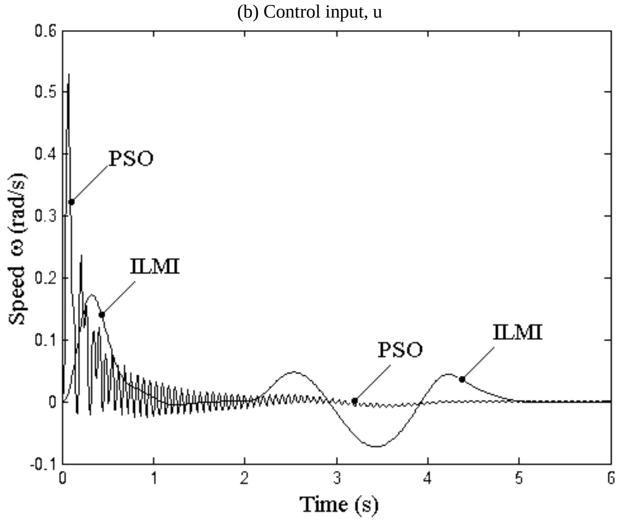
Wind gust is a sudden and brief increase in wind speed. To test the robustness to the wind speed variation, a gust shown in Fig. 8(a) is applied between 2-4 seconds. Fig. 8 shows the above mentioned variables behavior following a change in T_{ref} by +10% from t=0 s. It is clear that ILMI shows smooth with higher overshoot as compared to PSO that shows faster response but with heavy oscillations. Both controllers exhibit stability following the appearance of the gust.



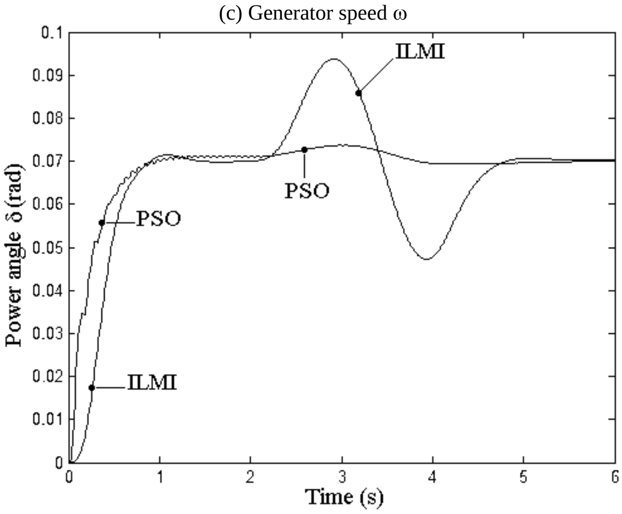
(a) Electromagnetic torque, T_e



(b) Control input, u



(c) Generator speed ω



(d) Power angle δ

Figure 8. Gust effect on system response

II. CONCLUSION

A PID controller is designed using two techniques, named, Particle Swarm Optimization (PSO) and Iterative Linear Matrix Inequalities (ILMI), and applied separately to drive a power system comprising a wind turbine and a synchronous generator connected to an infinite bus via a step-up transformer and a transmission line. Both designed controllers exhibit stability to the applied tests. The ILMI shows smoother but slower response whereas PSO shows faster one with heavy oscillations that need to be absorbed by the use of, for example, a Power System Stabilizer (PSS).

The advantages of one method with respect to the other depend on the designer needs and constraints. The system design is done for one operating point, it is worth looking into adapting the controllers to different operating points.

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APPENDIX

TABLE III.
OPERATING CONDITIONS

infinite bus voltage	V_∞=1
reactive power	Q=0.6
active power	P=0.8
gear ratio	N=37.5
Torque factor:	k_{th}=11.86
System constants:	k_1=2.492441223
	k_2=2.514312798
	k_3=0.082959641
	k_4=5.141769761

TABLE IV.
SYSTEM DATA

transmission line resistance	r_e=0
transmission line reactance	x_e=0.02
r.p.m	n_r=40
lade radius	r_b=62.5
wind speed m/sec	v_p=18
no. of poles	pp=4
inertia constant	h=9.5
conventional integral power controller gain	k_p=0.075
zeta	ζ=0.02
exciter time constant	τ=0.05
exciter gain	k_e=30
P.F controller gain	k_{pf}=0.2
generator armature resistance	r_a=0.018
d-axis reactance	x_d=2.21
q-axis reactance	x_q=1.064
transient d-axis reactance	x_d'=0.165
subtransient d-axis reactance	x_d''=0.128
subtransient q-axis reactance	x_q''=0.193
d-axis transient field time constant	τ_{do}'=1.94212
d-axis subtransient field time constant	τ_{do}''=0.01096
q-axis subtransient field time constant	τ_{qo}''=0.0623
angular speed of the generator [rad/sec]	ω_o=100π
ω_n	ω_n=100
wind turbine filter time constant	τ_p=1/(2*2.7*π)
Torque factor	k_{th}=11.86

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Dr. Bensenouci was awarded distinguished lecturer of the academic year 2000/2001. He published more than 90 papers in divers local and international Conferences and Technical Journals. He was the general secretary of the 1st Baha Technical Meeting, BTM'2004, Baha, KSA, May 3-5, 2004.