PARAMETER OPTIMIZATION OF PITCH CONTROLLER FOR ROBUST FREQUENCY CONTROL IN AN ISOLATED WIND-DIESEL HYBRID POWER SYSTEM USING GENETIC ALGORITHM

Cuk Supriyadi Ali Nandar
Badan Pengkajian dan Penerapan Teknologi (BPPT)
Jl.MH Thamrin No.8 Jakarta Pusat
e-mail: cuk_supriyadi@webmail.bppt.go.id

Abstract
This paper focuses on the parameter optimization of the pitch controller for robust frequency control in an isolated wind-diesel hybrid power system. The structure of the pitch controller is a practical 1st–order lead-lag compensator. In system modeling, the normalized coprime factorization is applied to represent system uncertainties such as variations of system parameters etc. As a result, the robust stability of the controlled system against various uncertainties can be guaranteed. To obtain the controller parameters, the performance and stability conditions of $H_\infty$ loop shaping control are employed to formulate the optimization problem. The genetic algorithm is used to solve the problem. The frequency control effect and robustness of the proposed pitch controller against system uncertainties are evaluated by simulation studies in comparison with a variable structure pitch controller.

Keywords: genetic algorithm, robust frequency control, wind-diesel hybrid power system

1. INTRODUCTION
Wind power is expected to be economically attractive when the wind speed of the proposed site is considerable for electrical generation and electric energy is not easily available from the grid [1]. This situation is usually found on islands and in remote localities. Nevertheless, wind power is intermittent due to worst case weather conditions such as an extended period of overcast skies or when there is no wind for several weeks. As a result, wind power generation is variable and unpredictable. To solve this problem, the hybrid wind power with diesel generation has been suggested [2-3].

A hybrid wind diesel system is very reliable because the diesel acts as a cushion to take care of variation in wind speed and would always maintain an average power equal to the set point. However, in addition to the unsteady nature of wind, another serious problem faced by the isolated power generation is the frequent change in load demands. This may cause large and severe oscillation of system frequency. In the worst case, the system may lose stability if
the system frequency can not be maintained in the acceptable range. To overcome this problem, the programmed pitch controller (PPC) in the wind side can be expected to be a cost-effective device for reducing frequency deviation. Over the years, several methods were proposed to design a PPC such as parameters optimization technique [4], conventional proportional integral controller [5-7], variable structure control [8], distributed control [9] etc. These controllers satisfactorily provide control effects.

However, the robustness of these controllers against system uncertainties such as system parameter variations, random load changes and unpredictable wind power input etc. has not been taken into account in the design process. The resulted controller may fail to operate and lose control effect under such system uncertainties. To improve the robustness of the PPC, the linear quadratic gaussian (LQG) controller with the loop transfer recovery (LTR) [11] and the hybrid neuro-fuzzy controller [12] have been applied to design the PPC. The presented controllers provide satisfactory robustness and damping effects on system frequency deviation. Nevertheless, these controllers have a complex structure which is not easy to realize in practical application. Most of industry applications still prefer simple controller such as PI, PID and lead-lag controller.

This paper is concerned with a parameter optimization of the robust PPC for frequency control in a hybrid wind-diesel system. The configuration of PPC is a 1st order lead-lag compensator. The normalized coprime factor is used to model system uncertainties [12-13]. The $H_\infty$ loop shaping technique is applied to formulate the optimization problem of controller parameters. The genetic algorithm (GA) [14] is applied to solve the problem. Simulation studies show the frequency control effect and the robustness of the proposed PPC and its superiority to the PPC designed by variable structure control [8].

2. SYSTEM MODELING

Fig. 1 shows the basic configuration of an isolated hybrid wind-diesel power generation system [8]. The PPC is installed in the wind side while the governor is equipped with the diesel side. In addition to the random wind energy supply, it is assumed that loads with sudden change have been placed in this isolated system. These result in a serious problem of large frequency deviation in the system. Such power variations and frequency deviations severely affect the system stability. Furthermore, the life time of machine apparatuses on the load side affected by such large frequency deviations will be reduced. For mathematical modelling, the transfer function block diagram of a hybrid wind-diesel power generation used in this study is shown in Fig. 2 [8]. The PPC is a 1st order lead-lag controller with single input feedback of frequency deviation of wind side.

![Diagram](image)

Fig. 1. Basic configuration of a hybrid wind-diesel power generation system.

The state equation in Fig. 2 can be expressed as
Parameter Optimization of Pitch Controller for Robust…… (Cuk Supriyadi Ali Nandar)

\[
\dot{\Delta X} = A\Delta X + B\Delta u_{ppc} \tag{1}
\]
\[
\Delta Y = C\Delta X + D\Delta u_{ppc} \tag{2}
\]
\[
\Delta u_{ppc} = K(s)\Delta f_w \tag{3}
\]

Where the state vector \(\Delta X = [\Delta f_w, \Delta P_D, \Delta P_I, \Delta H_I, \Delta H_2, \Delta P_p]\), the output vector \(\Delta Y = [\Delta f_w]\), \(\Delta U_{ppc}\) is the control output of the PPC. The proposed control is applied to design a robust PPC \(K(s)\). The system (1) is referred to as the nominal plant \(G_p\).

3. PROPOSED METHOD

In this section, the design procedure is explained. Each design step is explained as follows.

**Step 1** Selection of weighting functions

As in the conventional \(H_\infty\) loop shaping design, the shaped plant is established by weighting functions. Because the nominal plant is an SISO system, the weighting functions \(W_1\) and \(W_2\) are chosen as

\[
W_1 = K_w \frac{s + a}{s + b} \quad \text{and} \quad W_2 = I \tag{4}
\]

Where \(K_w\), \(a\) and \(b\) are positive values. Because, the frequency control problem is in a vicinity of low frequency \((< 1 \ \text{Hz})\) [5,6], \(W_1\) is set as a high-pass filter \((a < b)\).

**Step 2** Formulate the shaped plant \(G_s\).
As shown in Fig. 3, a pre-compensator $W_1$ and a post-compensator $W_2$, are employed to form the shaped plant $G_s = W_1 G W_1'$, which is enclosed by a solid line. The designed robust controller $K = W_1' K_s W_2$ is enclosed by a dotted line where $K_s$ is the $H_\infty$ controller.

**Step 3** Evaluate the robust stability margin of the system

A shaped plant $G_s$ is expressed in form of normalized left coprime factor $G_s = M_s^{'-1} N_s$, when the perturbed plant $G_\Delta$ is defined as

$$G_\Delta = \left( (M_s + \Delta M_s)^{-1} (N_s + \Delta N_s) : \| \Delta N_s \|_{\infty} \leq 1/\gamma \right)$$

Where $\Delta M_s$ and $\Delta N_s$ are stable unknown transfer functions which represent uncertainties in the nominal plant model $G$. Based on this definition, the $H_\infty$ robust stabilization problem can be established by $G_\Delta$ and $K$ as depicted in Fig. 4.

![Fig. 3. Shaped plant $G_s$ and designed robust controller $K$.](image1)

![Fig. 4. $H_\infty$ robust stabilization problem.](image2)

The objective of robust control design is to stabilize not only the nominal plant $G$ but also the family of perturbed plant $G_\Delta$. In (5), $1/\gamma$ is defined as the robust stability margin. The maximum stability margin in the face of system uncertainties is given by the lowest achievable value of $\gamma$, i.e. $\gamma_{\min}$. Hence, $\gamma_{\min}$ implies the largest size of system uncertainties that can exist without destabilizing the closed-loop system in Fig. 3. The value of $\gamma_{\min}$ can be easily calculated from

$$\gamma_{\min} = \sqrt{1 + \lambda_{\max}(XZ)}$$

Where $\lambda_{\max}(XZ)$ denotes the maximum eigenvalue of $XZ$. For minimal state-space realization $(A, B, C, D)$ of $G_s$, the values of $X$ and $Z$ are unique positive solutions to the generalized control algebraic Riccati equation

$$(A - BS^{-1}D^T C)^T X + X (A - BS^{-1}D^T C) - XBS^{-1}B^T X + C^T R^{-1} C = 0$$

and the generalized filtering algebraic Riccati equation

$$(A - BS^{-1}D^T C)Z + Z (A - BS^{-1}D^T C)^T - ZC^T R^{-1} CZ + BS^{-1} B^T = 0$$

where $R = I + DD^T$ and $S = I + D^T D$. Note that no iteration on $\gamma$ is needed to solved for $\gamma_{\min}$. To ensure the robust stability of the nominal plant, the weighting function is selected so that $\gamma_{\min} \leq 4.0$ [12]. If $\gamma_{\min}$ is not satisfied, then go to step 1, adjust the weighting function.
Step 4 Generate the objective function for GA optimization.

In this study, the performance and robust stability conditions in $H_\infty$ loop shaping design approach is adopted to formulate the optimization problem of controller parameters. The PPC is represented by

$$K = \frac{sT_1 + 1}{sT_2 + 1}$$  \hspace{1cm} (9)

The control parameters $K_c$, $T_1$, and $T_2$ are optimized based on the following concept. As shown in Fig. 3, the designed robust controller $K$ can be written as

$$K = W_iK_wW_2$$  \hspace{1cm} (10)

Because $W_2 = I$, $K_w$ controller can be written as

$$K_w = W_i^{-1}K$$  \hspace{1cm} (11)

As given in [13], the necessary and sufficient condition of the robust controller $K$ is

$$\begin{bmatrix} I \\ K_w \end{bmatrix} (I - G_iK_w)^{-1} \begin{bmatrix} I & G_i \end{bmatrix} \leq \gamma$$  \hspace{1cm} (12)

Substituting (11) into (12) yields

$$\begin{bmatrix} I \\ W_i^{-1}K \end{bmatrix} (I - G_iW_i^{-1}K)^{-1} \begin{bmatrix} I & G_i \end{bmatrix} \leq \gamma$$  \hspace{1cm} (13)

This condition can be formulated as the objective function in the optimization problem as

Minimize $$\begin{bmatrix} I \\ W_i^{-1}K \end{bmatrix} (I - G_iW_i^{-1}K)^{-1} \begin{bmatrix} I & G_i \end{bmatrix}$$  \hspace{1cm} (14)

Subject to

$$K_{c_{\min}} \leq K_c \leq K_{c_{\max}}$$

$$T_{1_{\min}} \leq T_1 \leq T_{1_{\max}}$$

$$T_{2_{\min}} \leq T_2 \leq T_{2_{\max}}$$  \hspace{1cm} (15)

Where $K_{c_{\min}}$ and $K_{c_{\max}}$ are minimum and maximum gains of PSS, $T_{1_{\min}}$ and $T_{1_{\max}}$, $i=1,2$ are minimum and maximum time constants of PPC. The optimization problem is solved by GA [14].

Step 5 Initialize the search parameters for GA. Define genetic parameters such as population size, crossover rate, mutation rate, and maximum generation.

Step 6 Randomly generate the initial solution.

Step 7 Evaluate objective function of each individual in (14).

Step 8 Select the best individual in the current generation. Check the maximum generation.

Step 9 Increase the generation.

Step 10 While the current generation is less than the maximum generation, create new population using genetic operators and go to step 8. If the current generation is the maximum generation, then stop.
3. SIMULATION STUDIES

In this section, simulation studies in a hybrid wind-diesel power generation are carried out. System parameters are given in [7]. Based on (4), the weighting functions are selected as.

\[ W_1 = \frac{s + 40}{s + 78}, \quad W_2 = I \]

(16)

Accordingly, the shaped plant \( G_s \) can be established. As a result, \( \gamma = 3.15 \). In the optimization, the ranges of search parameters and GA parameters are set as follows: \( K_c \in [1 \text{ to } 150] \), \( T_i \) and \( T_d \in [0.0001 \text{ to } 1] \), crossover probability is 0.9, mutation probability is 0.05, population size is 100 and maximum generation is 100. Consequently, the convergence curve of the objective function can be shown in Fig. 5. As a result, the designed PPC is

\[ K(s) = \frac{0.4600s + 1}{0.0870s + 1} \]

(17)

In simulation studies, the performance and robustness of the proposed controllers are compared with those of the PPC designed by the variable structure control (VSC) obtained from [7], that is

\[ U_{\text{VSC PPC}} = -K_p \Delta P_w \quad \text{if} \quad |\Delta P_w| > \epsilon \]

(18)

and when the error is small value the control law is selected as

\[ U_{\text{VSC PPC}} = -K_p \Delta P_w - K_i \int_{0}^{t} \Delta P_w \, dt \quad \text{if} \quad |\Delta P_w| \leq \epsilon \]

(19)

Where \( \epsilon = 0.0004, \quad K_c = 10, \quad K_i = 10 \) and \( K_i = 4 \). Here this controller is called “VSC PPC”.

In simulation studies, the limiter \(-0.01 \leq \Delta u_{\text{ppc}} \leq 0.01 \) pukW on system base of 350kW is equipped at the output terminal of the PPC. This implies that the power capacity of the PPC is 3.5 kW.

Simulation results under four case studies are carried out as follows.

**Case 1: Step input of wind power or load change**

First, a 0.01 pukW step increase in the wind power input is applied to the system at \( t = 0.0 \text{ s} \). Fig. 6 shows the frequency deviation of the diesel generation side which represents the system frequency deviation. Without PPC, the frequency deviation is very large. The frequency deviation takes about 15 s. to reach steady-state. On the other hand, the peak frequency deviation is reduced significantly and returns to zero within 5 s in case of the VSC PPC and the proposed PPC. Next, a 0.01 pukW step increase in the load power is applied to the system at \( t = 0.0 \text{ s} \). As depicted in Fig. 7, the proposed PPC is able to damp the peak frequency deviation.
quickly in comparison to without PPC and with VSC PPC cases. The frequency deviation reaches zero value in the shortest period.

**Case 2: Random wind power input.**

In this case, the system is subjected to the random wind power input as shown in Fig. 8. The system frequency deviations under normal system parameters are shown in Fig. 9. By the proposed PPC, the frequency deviation is significantly reduced in comparison to that of the VSC PPC. Next, the robustness of the proposed PPC is evaluated by an integral absolute error (IAE) under variations of system parameters.

For 60 seconds of simulation study under the same random wind power in Fig. 8, the IAE of the system frequency deviation is defined as IAE of

\[
\text{IAE of } \Delta f_D = \int_0^{60} |\Delta f_D| \, dt
\]  

Fig. 10 shows the values of IAE when the values of inertia constant of both wind and diesel sides are varied from -30 % to +30 % of the normal values. The values of IAE in case of the VSC PPC increase as inertia constant decreases. In contrast, the values of IAE in case of the proposed PPC are lower and rarely change. Next, when the governor gain \( K_G \) is changed
from -30 % to +30 % of the normal value, the variation of IAE is depicted in Fig. 11. The values of IAE in case of the VSC PPC highly increase when $K_d$ decreases while the IAE values of the proposed PPC slightly change. These results indicate that the proposed PPC is rarely sensitive to these parameter variations under this random wind power input.

Case 3: Random load change.

The random load change as shown in Fig.12 is applied to the system. Fig. 13 depicts the system frequency deviation under normal system parameters. The control effect of the proposed PPC is better than that of the VSC PPC.

Case 4: Simultaneous random wind power and load change.

In this case, the random wind power input in Fig. 8 and the load change in Fig.12 are applied to the system simultaneously. The system frequency deviation under normal system parameters are shown in Fig. 16. The frequency control effect of the proposed PPC is superior to that of the VSC PPC. Furthermore, when $K_d$ is reduced by 30 % from the normal value, the control effect of the VSC PPC is significantly deteriorated as depicted in Fig.17. On the other
hand, the frequency deviation is robustly reduced by the proposed PPC. The values of IAE of system frequency under the variation of inertia constant of both sides from -30 % to +30 % of the normal values are shown in Fig.18. As inertia constant decreases, the values of IAE in case of the VSC PPC highly increase. On the other hand, the values of IAE in case of the proposed PPC are much lower and almost constant. In addition, when $K_d$ is changed from -30 % to +30 % of the normal value, the same tendency of IAE variation is also achieved as in Fig.19. These results confirm that the proposed PPC is very robust against these variations of system parameter under both random wind power input and load change.
4. CONCLUSION

In this study, a parameter optimization of the robust programmed pitch controller for frequency control has been proposed in the hybrid wind-diesel power system. The controller is based on the practical 1st-order lead-lag compensator. The performance and stability conditions of $H_\infty$ loop shaping technique have been applied as the objective function in the parameter optimization problem. The GA has been used to automatically tune the control parameters of the pitch controller. Simulation results confirm that the proposed pitch controller is superior to the VSC PPC in terms of the robustness against various uncertainties. With low order controller and single feedback input, satisfactory control effect and high robustness, the proposed controller can be highly expected to implement in real systems.

REFERENCES