LOAD FREQUENCY CONTROL OF ISOLATED WIND DIESEL HYBRID POWER SYSTEMS

T. S. BHATTI, A. A. F. AL-ADEMI and N. K. BANSAL
Centre for Energy Studies, Indian Institute of Technology, New Delhi 110 016, India

(Received 19 December 1995)

Abstract—In this paper, a load frequency controller is designed for isolated wind Diesel hybrid power systems, and its effect on the transient performance of the system is evaluated. The modelling of the system, consisting of a wind turbine induction generator unit and a Diesel engine synchronous alternator unit, is presented along with the controller, both for continuous and discrete control cases. Optimum parameter values are obtained for different hybrid power system examples with continuous and discrete load frequency control and with and without blade pitch controllers, using the integral square error criterion (ISE). It is shown that wind Diesel or multi-wind Diesel hybrid power systems, with blade pitch control mechanism and with continuous load frequency control, have better dynamic performance than any other configuration of the isolated wind Diesel hybrid systems. Finally, some of the transient responses of the systems are shown for optimum gain settings.

INTRODUCTION

Hybrid wind Diesel stand-alone power systems are considered economically viable in many cases for supply of electric energy to remote and isolated places (hilly areas and islands) where the wind speed is considerable for electric generation, and also, electric energy is not easily available from the grid [1–8]. If the generation is available, the successful operation of the hybrid power system depends largely on the engineer's ability to provide reliable and uninterrupted service to the consumer's load. It implies that the system frequency be held within close tolerances so that the consumer's equipment may operate satisfactorily, and also, the operator must maintain high standards of continuous electrical service. Wind energy is intermittent, and also, the real power demand of the isolated community changes frequently. It is, therefore, necessary to have a proper control strategy for maintaining the scheduled frequency and nullify the offset, if any, between generation and load.

Different strategies can be adopted to reduce the mismatch between the generation and load and, thereby, control the system frequency deviations. The strategies are, namely, dump load control, priority switched load control, flywheel energy storage systems, superconducting magnetic energy storage systems and battery energy storage systems [5–11]. The dump load control system maintains the frequency at the desired level by adjusting the bleeder load, and the excess energy to the load is wasted as heat. In the priority switched load control system, on/off switches are provided to different priority loads. The control action is to schedule the load, as per the priority, and to match the generation. Though the control is simple, the steady state deviation in frequency may be large, and also, the supply to all types of loads may not be continuous. The next two energy storage systems may be capable of reducing the transient peak following a disturbance, but these are not capable of altering generation or load so as to reduce the frequency deviation to a minimum. The battery storage system is capable of maintaining the scheduled frequency by storing or delivering energy as per requirements of the system, but battery storage has a short life, poor efficiency and is maintenance intensive.

The load frequency control is to maintain the power balance in the system such that the frequency deviates from its nominal value to within specified bounds and according to practically acceptable dynamic performance of the system [12]. The control strategy evolved here may also result in overall high efficiency (fuel saving) and minimum additional equipment to avoid cost.
maintenance etc. The supplementary controller of the Diesel generating unit, called the load frequency controller, may satisfy these requirements. The function of the controller is to generate, raise or lower command signals to the speed-gear changer of the Diesel engine in response to the frequency error signal by performing mathematical manipulations of amplification and integration of the signal. The speed-gear changer must not act too fast, as it will cause wear and tear of the engine and, also, should not act too slow, as it will deteriorate the system performance. Therefore, an optimum load frequency controller is required for satisfactory operation of the system.

In the present work, a detailed study has been performed for hybrid wind Diesel isolated power systems by considering a small signal transfer function model. Optimum selection of the gains of the controllers is obtained using the ISE technique both for continuous and discrete control cases. The results are presented for different sampling periods, including some transient responses of the system.

**SYSTEM MODELLING**

The function of the load frequency controller is to eliminate a mismatch created either by the small real power load change or due to a change in input wind power. The input power to the wind power generating unit is not controllable in the sense of generation control, but a supplementary controller, known as the load frequency controller, can control the generation of the Diesel power generating unit and, thereby, of the system. The small real power mismatch causes a perturbation about the nominal operating point, and therefore, the system dynamics may be described by linear differential equations [4, 6, 13–17]. The transfer function block diagram of the system is shown in Fig. 1, which includes the load frequency controller and also the blade pitch controller. The dynamics of the wind power generating unit is described by a first order system. A higher order model can, however, be considered if the slow dynamics of the mechanical parts are to be incorporated [16, 17]. The continuous time dynamic behaviour of the load frequency control system is modelled by a set of state vector differential equations.

\[
\dot{X} = AX + Bu + Gp
\]  

(1)

where \(X\), \(u\) and \(p\) are the state, control and disturbance vectors, respectively. \(A\), \(B\) and \(G\) are real constant matrices, of the appropriate dimensions, associated with the above vectors. The matrices and vectors are defined in Appendix 1.

**LOAD FREQUENCY CONTROLLER MODELLING**

(i) Continuous case

In order to design the load frequency controller of proportional plus integral type for the system

---

Fig. 1. Transfer function block diagram representation of an isolated wind Diesel system with controllers.
so as to achieve zero steady state error in frequency, the state vector in equation (1) is to be augmented by two additional state variables \( x_{s+1} \) and \( x_{s+2} \) defined as

\[
x_{s+1} = \int \Delta f_s \, dt
\]

\[
x_{s+2} = \int \Delta f_r \, dt.
\]

Therefore, the additional state differential equations are

\[
\dot{x}_{s+1} = \Delta f_s
\]

\[
\dot{x}_{s+2} = \Delta f_r.
\]

Equations (4) and (5) can be written in matrix form as

\[
\begin{bmatrix}
\dot{x}_{s+1} \\
\dot{x}_{s+2}
\end{bmatrix} = A_1 \bar{X}.
\]

Now, the state vector in equation (1) is modified by including the state variables defined in equations (2) and (3). The augmented set of differential equations can be written as

\[
\dot{\bar{X}} = \begin{bmatrix}
A & 0_1 \\
A_1 & 0_2
\end{bmatrix} \bar{X} + \begin{bmatrix}
B \\
0_3
\end{bmatrix} u + \begin{bmatrix}
\Gamma \\
0_4
\end{bmatrix} p,
\]

where \( 0_1, 0_2, 0_3, \) and \( 0_4 \) are null matrices of appropriate dimensions. The control vector \( u \) can be expressed in terms of the augmented state vector as

\[
u = H \bar{X},
\]

where

\[
H = \begin{bmatrix}
-K_{sp} & 0 & 0 & 0 & 0 & 0 & -K_{sg} & 0 \\
K_{ig} & K_{ip} & 0 & 0 & -K_{ig} & K_{ip} & 0 & 0
\end{bmatrix}.
\]

The final augmented set of differential equations can be written as

\[
\dot{\bar{X}} = \bar{A} \bar{X} + \bar{f} p,
\]

where

\[
\bar{A} = \begin{bmatrix}
A & 0_1 \\
A_1 & 0_2
\end{bmatrix} + \begin{bmatrix}
B \\
0_3
\end{bmatrix} H \quad \text{and} \quad \bar{f} = \begin{bmatrix}
\Gamma \\
0_4
\end{bmatrix}.
\]

(ii) Discrete case

In discrete load frequency control, the system is continuous, but the control input to the system changes to a new value at a certain discrete interval and remains constant during the interval. The system dynamics is continuous as described by equation (1). Therefore, the solution of the differential equations can be obtained by numerical integration methods, along with the discrete control inputs computed as described below. Equations (2) and (3) represent the area under the respective curves. At time, \( t \), it can be expressed as

\[
x_{s+1}(t + \Delta t) = \frac{\Delta f_s(t + \Delta t) - \Delta f_s(t)}{2} \Delta t + x_{s+1}(t)
\]

\[
x_{s+2}(t + \Delta t) = \frac{\Delta f_r(t + \Delta t) - \Delta f_r(t)}{2} \Delta t + x_{s+2}(t),
\]

where \( \Delta t \) is the numerical integration step time for the continuous time system. In the discrete case, the control inputs to the system change in discrete steps, \( T_s (=m \Delta t, m = \text{no. of continuous time} \)
Table 1. Rating and data of the three examples of the isolated power system studied

<table>
<thead>
<tr>
<th>Sys. No.</th>
<th>Wind Generator (Kw)</th>
<th>Turbine Generated (Kw)</th>
<th>Diesel (Kw)</th>
<th>Load (Kw)</th>
<th>Kp (Hz/puKw)</th>
<th>Tp (s)</th>
<th>Ku (puKw/Hz)</th>
<th>K0 (puKw/Hz)</th>
<th>Kp0 (puKw/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>—</td>
<td>—</td>
<td>150</td>
<td>72.00</td>
<td>14.4</td>
<td>1.494</td>
<td>0.4</td>
<td>0.00430</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>—</td>
<td>650</td>
<td>150</td>
<td>81.43</td>
<td>16.3</td>
<td>0.272</td>
<td>0.64</td>
<td>0.0014</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>150</td>
<td>650</td>
<td>150</td>
<td>81.43</td>
<td>16.3</td>
<td>0.272</td>
<td>0.64</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

T1 = 1.000 s, T2 = 2.00 s, T3 = 0.025 s, T4 = 3.00 s, K0 = 5.000 Hz/puKw, T5 = 4.00 s, Kp0 = 0.080 puKw/deg, Kp1 = 1.25, T6 = 0.600 s, Kp2 = 1.00, T7 = 0.041 s, Kp3 = 1.40, T8 = 1.000 s, Kp4, Kp5, Kp6 = 1.75 deg/puKw.

control intervals), and during the intervals, it remains constant. Therefore, if the proportional integral control strategy is used, the control vector at time kT is given by

\[ u_k(kT) = -K_{PI}\Delta f_s(kT) - K_{PI}C(kT) \]

(12)

\[ u_k(kT) = -K_{IG}K_{PI}\{\Delta f_s(kT) - \Delta f_s(kT) \} \]

(13)

where \( k = 0, 1, 2, 3 \ldots \) etc.

PARAMETER OPTIMIZATION

Optimization of the load frequency controller gains and proportional and integral gains of the blade pitch control mechanism is performed by using the integral square error criterion and is given by

\[ \eta = \int_0^\infty [\Delta f_s(t)]^2 \, dt. \]

(14)

SIMULATION RESULTS

The simulation results discussed in this section are for three examples of the wind Diesel power system with or without multiplicity of generation. The data of the three examples considered is given in Table 1. The gains of the blade pitch control mechanism and of the load frequency controller have been optimized both for the continuous and discrete control cases. The optimum

Table 2. Optimum values of the blade pitch controller gains and of the load frequency controller gains

<table>
<thead>
<tr>
<th>System Ex. No</th>
<th>Type of control</th>
<th>Wind</th>
<th>Diesel</th>
<th>Kp0</th>
<th>Ku</th>
<th>K0</th>
<th>Kp0</th>
<th>K0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>cont. cont.</td>
<td>53.00</td>
<td>1.20</td>
<td>266.45</td>
<td>20.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cont. disc. (0.02 s)</td>
<td>47.00</td>
<td>0.84</td>
<td>187.40</td>
<td>17.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.01 s)</td>
<td>49.25</td>
<td>1.00</td>
<td>221.85</td>
<td>19.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.02 s)</td>
<td>45.00</td>
<td>0.86</td>
<td>187.00</td>
<td>17.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.03 s)</td>
<td>42.25</td>
<td>0.80</td>
<td>162.21</td>
<td>16.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cont. disc. (0.01 s)</td>
<td>—</td>
<td>—</td>
<td>266.70</td>
<td>20.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cont. disc. (0.02 s)</td>
<td>—</td>
<td>—</td>
<td>221.50</td>
<td>19.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cont. disc. (0.03 s)</td>
<td>—</td>
<td>—</td>
<td>186.40</td>
<td>17.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cont. disc. (0.01 s)</td>
<td>—</td>
<td>—</td>
<td>161.80</td>
<td>16.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>cont. cont.</td>
<td>214.0</td>
<td>10.5</td>
<td>48.00</td>
<td>-0.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.01 s)</td>
<td>160.5</td>
<td>14.40</td>
<td>40.80</td>
<td>-0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.02 s)</td>
<td>141.0</td>
<td>13.05</td>
<td>36.33</td>
<td>-0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>cont. cont.</td>
<td>202.3</td>
<td>11.20</td>
<td>81.60</td>
<td>-0.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.01 s)</td>
<td>165.0</td>
<td>11.70</td>
<td>69.10</td>
<td>-0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>disc. (0.02 s)</td>
<td>157.0</td>
<td>12.30</td>
<td>59.90</td>
<td>-0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

†Without blade pitch control mechanism.
values of these gains are given in Table 2. Using the optimum values, different transient responses are obtained, as shown in Figs 2-14, for a step increase in load or for a step increase in input wind power.

Figures 2 and 3 show the deviation in frequency, $\Delta F_s$, Diesel power generation, $\Delta P_{DG}$, and wind power generation, $\Delta P_{GW}$, for system example 1, with continuous and discrete time load frequency

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{System transient response curves for (a) change in system frequency (b) change in diesel power generation (c) change in wind power generation for 1% step increase in input load with --- continuous time control, - - - - discrete time control $T_r = 0.01$ s, - - - - - discrete time control $T_r = 0.03$ s.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{System transient response curves for (a) change in system frequency (b) change in diesel power generation (c) change in wind power generation for 1% step increase in input load with --- continuous time control, - - - - discrete time control $T_r = 0.01$ s, - - - - - discrete time control $T_r = 0.03$ s.}
\end{figure}
controls. It is observed that, for a step increase in input wind power, the blade pitch control mechanism brings the deviation $\Delta C_{\text{m}}$ to zero with a settling time of about 12 s, where $\Delta F_2$ and $\Delta P_{\text{co}}$ also become zero. This shows that the wind power generation cannot be raised from the maximum power generation set-point and the blade pitch control mechanism becomes active for any increase beyond this set-point in the input wind power. For a step increase in real power demand, it is observed that the transients settle within 4 s. following the disturbance, and the load frequency control eliminates a mismatch between the generation and load. Transient responses with discrete control intervals $T_s = 0.01$ and 0.03 s. are also shown in the figures. The frequency responses show that the amplitude of the first swing is more compared to the case of continuous control with a small increase in settling time also.

Next, the same power system example is considered for simulation but without a blade pitch control mechanism. The transient responses for this system are shown in Figs 4–6. It is observed that the amplitude of the first swing is the same, but the settling time is more, of the order of 23 s. in comparison to 12 s. of the system with a blade pitch controller. A comparison of the responses for the continuous case, as shown in Figs 3, 4 and 6, demonstrates that the performance of the system without a blade pitch control mechanism is the same for a step change in load as the system with a blade pitch controller. In this case, it is also observed from the responses that the performance deteriorates with the discrete load frequency controller.

Figures 7–9 show the transient response curves for system example 2 of multi-Diesel and wind hybrid electric power system. Though both the Diesel units have their own speed governing mechanisms, only the higher rating Diesel power generating unit is considered to be equipped with a load frequency controller. Figures 10–14 show the transient response curves for system example 3 of multi-wind and Diesel hybrid power system. In this case also, one of the wind turbines is

---

![Graph](image1)

*Fig. 4. System transient frequency response curves for 1% step increase in (a) input wind power (b) load, with the absence of wind turbine blade pitch controller, with --- continuous time control, - - - discrete time control $T_i = 0.02$ s.*

![Graph](image2)

*Fig. 5. Transient response curves for change in power generation for 1% step increase in input wind power without blade pitch controller, with — continuous time control, $\Delta F_{\text{co}}$; --- continuous time control, $\Delta P_{\text{m}}$.***
Fig. 6. Transient response curves for change in power generation of system without blade pitch controller for 1% step increase in load, with — continuous time control, \( \Delta P_{\text{cbd}} \), —- continuous time control, \( \Delta P_{\text{cow}} \); —— discrete time control, \( \Delta P_{\text{cbd}} \), —— discrete time control, \( \Delta P_{\text{cow}} \). \( T_i = 0.02 \, \text{s}, \Delta P_{\text{cow}}, \Delta P_{\text{cbd}} \).

Fig. 7. System transient frequency response curves for 1% step increase in (a) input wind power (b) and (c) load, with — continuous time control, —- continuous time control, —— discrete time control, \( T_i = 0.02 \, \text{s} \).

Fig. 8. Transient response curves for change in power generation with continuous time control for 1% step increase in load. — \( \Delta P_{\text{cbd}} \), —- \( \Delta P_{\text{cow}} \), —— \( \Delta P_{\text{cow}} \).

Fig. 9. Transient response curves for change in power generation for 1% step increase in load, with — continuous time control, \( \Delta P_{\text{cbd}} \); —— discrete time control, \( T_i = 0.02 \, \text{s}, \Delta P_{\text{cow}} \); —— discrete time control, \( \Delta P_{\text{cow}} \).

Fig. 10. System transient frequency response curves for 1% step increase. In (a) input wind power (b) and (c) load, with — continuous time control, —- continuous time control, —— discrete time control \( T_i = 0.02 \, \text{s} \).

Fig. 11. Transient response curves for change in power generation with cont. time control for 1% step increase in input wind power. — \( \Delta P_{\text{cbd}} \), —- \( \Delta P_{\text{cow}} \), —— \( \Delta P_{\text{cow}} \).
not equipped with the blade pitch control mechanism. It is observed from the responses, shown in Figs 7–14, for optimum controller gains that the dynamic performance of the multi-wind system is better compared to the multi-Diesel system. It is observed that the discrete load frequency controller again has a deteriorating effect on the system dynamic performance. Finally, from the responses, under steady state conditions, it is clear that the load frequency controller functions satisfactorily by nullifying the mismatch between the generation (wind + diesel) and the load.

CONCLUSIONS

A transient performance study of the isolated wind Diesel hybrid power system with load frequency controller installed on the Diesel unit and the wind turbine unit equipped with a blade pitch control mechanism have been presented. For investigation of the results, two examples of multi-wind and of multi-Diesel units have also been considered. The controller gains have been optimised for the power system examples under consideration, both for continuous and discrete load frequency control of the system using the mathematical models of the controller derived in this paper. The results obtained prove that, for changes in input wind power, the transient performance of the system is better when it is equipped with a blade pitch control mechanism, but for changes in load, the transient performance of the system remains unaffected, as it is accomplished by the load frequency controller installed on the Diesel unit. The performance of
the hybrid system with multi-wind units has been observed to be better compared to that with multi-Diesel units. It has also been shown that the transient performance of the continuous system deteriorates with the discrete load frequency control of the system. In conclusion, therefore, the wind Diesel or multi-wind Diesel hybrid power systems having a blade pitch control mechanism and continuous load frequency controller have, overall, the best transient performance.

REFERENCES


APPENDIX

The elements of the matrices in equation (1) and the associated state vectors are given below:

\[
\begin{align*}
X &= \begin{bmatrix}
\Delta P_{CG}
\Delta X_{CG}
\Delta X_{CG}
\Delta X_{CG}
\end{bmatrix}^T \\
U &= \begin{bmatrix}
\Delta P_{CG}
\Delta X_{CG}
\end{bmatrix}^T \\
p &= \begin{bmatrix}
\Delta P_{CG}
\Delta X_{CG}
\end{bmatrix}^T
\end{align*}
\]

\[
A(1, 1) = -(1 + K_{CG} K_{CG}) / T_r
\]

\[
A(1, 2) = K_{CG} / T_r
\]

\[
A(1, 5) = K_{CG} K_{CG} / T_r
\]

\[
A(2, 2) = -1.0 / T_{DS}
\]

\[
A(2, 3) = 1.0 / T_{DS}
\]

\[
A(2, 4) = 1.0 / T_{DS}
\]

\[
A(3, 1) = -K_{CG} (T_{DS} - T_{DS}) / [K_{CG} (T_{DS} - T_{DS})]
\]

\[
A(3, 3) = -1.0 / T_{DS}
\]

\[
A(4, 1) = -K_{CG} (T_{DS} - T_{DS}) / [K_{CG} (T_{DS} - T_{DS})]
\]

\[
A(4, 4) = -1.0 / T_{DS}
\]

\[
A(5, 1) = K_{CG} / T_{DS}
\]

\[
A(5, 5) = -1.0 - K_{DS} + K_{CG} / T_{DS}
\]

\[
A(6, 6) = 1.0
\]

\[
A(6, 7) = K_{CG} K_{CG} / T_{DS}
\]

\[
A(6, 8) = K_{CG} K_{CG} / T_{DS}
\]

\[
A(7, 7) = -1.0
\]

\[
A(7, 8) = 1.0 / T_{DS}
\]

\[
B(3, 1) = K_{CG} (T_{DS} - T_{DS}) / [K_{CG} (T_{DS} - T_{DS})]
\]

\[
B(4, 1) = K_{CG} (T_{DS} - T_{DS}) / [K_{CG} (T_{DS} - T_{DS})]
\]

\[
B(8, 2) = K_{CG} / T_{DS}
\]

\[
\gamma(1, 1) = -K_{CG} / T_{DS}
\]

\[
\gamma(5, 2) = 1.0 / T_{DS}
\]