A Frequency Control Method for Isolated Photovoltaic-diesel Hybrid Power System with Use of Full Renewable Energy

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Abstract — In this paper, a frequency control method is introduced for photovoltaic-diesel hybrid system by using a load estimator and an energy storage system. The proposed method is compared with a fuzzy based frequency control method. Simulation results show that the proposed method is feasible to reduce the frequency deviations of the isolated power utility and delivers maximum power compared to the fuzzy based method.

Index Terms—Frequency control, photovoltaic-diesel hybrid power system, load estimator, energy storage system, frequency deviation.

I. INTRODUCTION

Most small islands around the world are still dependent on imported fossil fuels for most of their energy requirements. The electricity of these islands is exclusively produced by diesel generators. The use of diesel generators to provide electricity is one of the most expensive and environmentally detrimental ways of generating electricity [1]. Although these islands produce only a tiny fraction of global clean house gas emissions, they are amongst the most vulnerable to the effects of climate change. So, there is a need to introduce renewable energy in isolated islands to reduce the diesel consumption.

Global photovoltaic (PV) production has been doubling every two years, increasing by an average of 48% each year since 2002, making it the world’s fastest growing energy technology [2]. One of the most promising applications of photovoltaic power system is the installation of PV-diesel hybrid systems in isolated islands where the cost of grid extension is prohibitive and the price for fuel increases drastically with the remoteness of the location. It is reported that in sunny locations, PV generators compare favorably with wind generators [3].

To date it has not been necessary for PV power systems to provide frequency control services to the isolated power utility. In the future, with an increasing penetration of PV generation, their impact upon the overall control of the power system will be significant [4]. This will lead to a situation where the PV generators will be required to share some of the duties, such as frequency control. Therefore, for the penetration of large PV power in the isolated utility without reducing the reliability of the utility, suitable measures must be applied to the PV systems side.

Several studies have been carried out for reducing the harmful effect of large PV power penetration. Power characteristics of PV ensembles are presented in [5] where monitored data from 100 PV systems were used to study effects of combined power generation of these systems, compared to the characteristics of an individual system. It was claimed that a significant amount of power fluctuations disappeared, however, large amount of short term power fluctuations are remained. In addition, when the numbers of PV power systems were decreased, the power fluctuations increased. Smoothing of PV system output by tuning maximum power point tracking (MPPT) control is demonstrated in [6]. In this method, when the insolation increases rapidly, the operating MPPT point changes to a new point where the maximum power is not generated with the current insolation. It was reported that this method can be applied to several PV power generation systems to achieve a combined output power fluctuations smoothing. However, the condition of power utilities like frequency deviation is not considered for tuning the MPPT and for limiting the new output voltage. Moreover, none of the above methods is used for frequency control purpose.

Recently, a fuzzy based frequency control method for PV-diesel hybrid system is introduced in [7]. Insolation, change of insolation, and frequency deviation are used as inputs for fuzzy controlled output power command system which decides the required PV output power to reduce frequency deviations.

In this paper, we introduce a frequency control method for PV-diesel hybrid system by using a load power estimator [8].
and an energy storage system (ESS) [9]. Our method is compared with the method described in [7] and is found effective in following key features: supplying MPPT generated PV power, reducing required diesel power so as the CO2 emission, and reducing frequency deviations.

II. MODEL OF ISOLATED POWER SYSTEM

The block diagram of the isolated power utility used in this paper is shown in Fig. 1. The isolated power utility consists of a diesel generator, a PV system, and an ESS that generate power to supply the load demand.

The detail model of the isolated power system consisted of a diesel generator, a PV generator, a load estimator, an ESS and load is shown in Fig. 2, where, \( S_i \) is the insulation, \( P_{pv} \) is the PV power, \( P_{max} \) is the MPPT power, \( P_d \) is the generated diesel power, \( R \) is the speed regulation, \( T_g \) is the governor time constant, \( T_d \) is the diesel generator time constants, \( P_L \) is the load, \( \hat{P}_L \) is the estimated load power, \( M \) is the inertia constant, \( D \) is the damping constant, \( P_{ESS} \) and \( P_{ESS}^* \) is the actual ESS power and command ESS power, \( u \) is the governor input, and \( \Delta f \) is the frequency deviation.

As the design of power converter and the control system is significantly influenced by the PV module characteristics, these will briefly reviewed here. The PV module is a nonlinear device and can be represented as a current source, these will briefly reviewed here. The PV module is a nonlinear device and can be represented as a current source, as shown in Fig. 3. The traditional I- V characteristics of a PV module are given by the following equation [10]:

\[
I_0 = N_p I_g - N_p I_{sat} \exp\left\{\frac{qV_0}{AKT_a}\left(V_0 + \frac{N_s R_s I_0}{N_p}\right)\right\} - I_{rsh} \tag{1}
\]

where \( I_0 \) and \( V_0 \) are the output current and output voltage of the PV module, respectively, \( I_g \) is the generated current under a given insolation, \( I_{sat} \) is the reverse saturation current, \( q \) is the charge of an electron, \( K \) is the Boltzmann’s constant, \( A \) is the ideality factor, \( T_a \) is the temperature of the PV array (K), \( N_p \) is the number of cells in parallel, \( N_s \) is the number of cells in series and \( I_{rsh} \) is the current due to intrinsic shunt resistance of the PV module.

The saturation current \( I_{sat} \) of the PV module varies with temperature according to the following equation [10]:

\[
I_{sat} = I_{or} \left[ \frac{T_a}{T_{ref}} \right]^{-3} \exp\left\{\frac{qE_g}{KT_a}\left(\frac{1}{T_{ref}} - \frac{1}{T_a}\right)\right\} \tag{2}
\]

\[
I_g = I_{sc} + I_s (T_a - T_{ref}) \frac{S_j}{1000} \tag{3}
\]

where \( I_{or} \) is the saturation current at \( T_{ref} \), \( T_{ref} \) is the reference temperature, \( E_g \) is the band gap energy, \( I_s \) is the short circuit current temperature coefficient, and \( I_{sc} \) is the short circuit current of PV module. The current due to the shunt resistance is given by the following equation [10]:
\[ I_{\text{sh}} = \frac{V_0 + N_s I_0 R_s}{N_s R_{\text{sh}}} \] (4)

where \( R_{\text{sh}} \) is the internal shunt resistance of the PV module. The PV module output power is given by the following equation:

\[ P_0 = V_0 I_0 \] (5)

For PV module, (1)-(5) are used in the development of MATLAB/SIMULINK based computer simulations. Figs. 4(a) and (b) show the simulated ampere-volt and power-volt curves for the PV module. Here, the discrete data points shown are taken from the manufacturer’s data sheet [11] for validating the model. From these curves, it is observed that the output characteristics of the PV array are nonlinear and are vitally affected by the variation of insolation.

III. LOAD POWER ESTIMATOR DESIGN

First, a minimal-order observer is designed to estimate the load power by using the power system parameters. A simple minimal-order observer [12] is shown in Fig. 5. The state space representation of the plant is obtained by

\[ \dot{x}(t) = Ax(t) + Bu(t) \] (1)

\[ y(t) = Cx(t) \] (2)

where \( x(t) \) is an \( n \times 1 \) state vector, \( y(t) \) is an \( l \times 1 \) output vector, \( u(t) \) is an \( m \times 1 \) input vector, \( A \) is an \( n \times n \) system matrix, \( B \) is an \( n \times m \) input matrix, and \( C \) is an \( l \times n \) output matrix.

From [12] and Fig. 6, the minimal-order state observer can be written as

\[ \dot{\hat{x}}(t) = \hat{A}\hat{x}(t) + \hat{B}u(t) \] (3)

\[ \dot{\hat{y}}(t) = \hat{D}\hat{x}(t) + \hat{H}y(t) \] (4)

where \( \hat{x}(t) \) is the \( n-l \times 1 \) state variable of the observer, \( D(n \times n-l) \), \( H(n \times l) \), \( \hat{A}(n-l \times n-l) \), \( \hat{K}(n-l \times l) \), and \( \hat{B}(n-l \times m) \) are design co-efficients in the minimal-order observer, and \( \hat{A} = A_{22} - LA_{12} \), \( \hat{K} = \hat{A}L + A_{21} - LA_{11} \), \( \hat{B} = -LB_1 + B_2 \), \( D = S^{-1}\left[ \begin{array}{c} \text{0} \\ \text{I}_{l-n} \text{I}_{l-n} \end{array} \right] \), and \( H = S^{-1}\left[ \begin{array}{c} \text{I}_{l} \\ \text{I}_{l} \end{array} \right] \).

\[ \hat{A} = \begin{bmatrix} 1.75 & 0.2 & -1.95 \\ -9.75 & -10 & 9.75 \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} 0 \\ 10 \end{bmatrix}, \quad \hat{D} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \text{and} \quad \hat{H} = \begin{bmatrix} 1 \\ -0.195 \\ 0.975 \\ -0.9 \end{bmatrix}, \quad \text{and} \quad \hat{A}L = -LB_1 + B_2 \]

\[ \hat{\omega}_1 = \begin{bmatrix} 1.75 & 0.2 & -1.95 \\ -9.75 & -10 & 9.75 \end{bmatrix}, \quad \hat{\omega}_2 = \begin{bmatrix} 9 \\ 0 \\ 9 \end{bmatrix}, \quad \hat{\omega}_3 = \begin{bmatrix} 9 \\ 0 \\ 9 \end{bmatrix}, \quad \hat{\omega}_4 = \begin{bmatrix} 9 \\ 0 \\ 9 \end{bmatrix} \] (5)

\[ \hat{\omega} = \begin{bmatrix} \hat{\omega}_1 \\ \hat{\omega}_2 \\ \hat{\omega}_3 \end{bmatrix} = \begin{bmatrix} 1.75 & 0.2 & -1.95 \\ -9.75 & -10 & 9.75 \end{bmatrix} \begin{bmatrix} 1 \\ -0.195 \\ 0.975 \\ -0.9 \end{bmatrix} \] (6)
IV. OUTPUT POWER COMMAND SYSTEM

After estimating load power, \( \hat{P}_L \), the required diesel power can be found by the following equation.

\[
P_{\text{dreq}} = \hat{P}_L - P^*_{\text{max}}
\]  

(7)

where \( P^*_{\text{max}} \) is the MPPT command power. The leveling diesel power can be obtained by the following equation.

\[
P_{\text{dlevel}} = \frac{1}{T_s} \int_{t-T_s}^{t} P_{\text{dreq}} \, dt
\]  

(8)

where \( T_s \) is the sampling time. Now the ESS charging/discharging power command is generated by the following equation.

\[
P^*_{\text{ESS}} = P_{\text{dreq}} - P_{\text{dlevel}}
\]  

(9)

If the sign of \( P^*_{\text{ESS}} \) is negative, ESS is in discharging mode. On the other hand, if the sign of \( P^*_{\text{ESS}} \) is positive, ESS is in charging mode. The ESS charging/discharging command system is shown in Fig. 7.

V. SIMULATION RESULTS

Effectiveness of the proposed frequency control method is examined by simulation with system model and parameters mentioned in [10], [11], [13], and [14]. In order to use the parameters of real systems given in [13], [14], the rated output powers of the PV generator and the diesel generator are 225 kW and 450 kW respectively. The rating of the ESS is 135 kW. Simulation parameters of power system, PV array, and power converter are shown in TABLE III. Integral time \( T \) is 100s, and sampling time \( T_s \) to obtain discrete value of output power command is 10s. Simulation time is 30 minutes.

Fig. 8(a) shows the actual load and estimated load by solid line and dotted line respectively. Fig. 8(b) shows the percentage of estimation error. The load estimator works well as the estimated values are in accordance with the actual values and the estimation error is less than 1%. Fig. 9 shows the comparative simulation results of the proposed method and the method given in [7]. Fig. 9(a) shows insolation which is pretty fluctuating with time. Figs 9 (b), (c), (d), and (e) show the comparative simulation results where results of the proposed method are shown by solid line and results of the fuzzy based method [7] are shown by dotted line respectively. Fig. 9(b) shows PV power where the power produced by the fuzzy based method is less than the power produce by the proposed method as proposed method supplies MPPT controlled PV power to the utility. Fig. 9(c) shows the diesel power where diesel power produced with the proposed method is less fluctuating than the diesel power produced with fuzzy based method. Moreover, lesser amount of diesel power is required with the proposed method; therefore, proposed method can reduce usage of heavy oil compared to the fuzzy based method. Fig. 9(d) shows frequency deviation where frequency deviation with the proposed method is almost zero. Fig. 9(e) shows ESS charging and discharging power.

![Fig. 8. Load power estimation](image)

![Fig. 8. Load power estimation error](image)

**TABLE III**

<table>
<thead>
<tr>
<th>Parameters of isolated power system</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia constant, ( M )</td>
<td>0.150 puMW.s/Hz</td>
</tr>
<tr>
<td>Damping constant, ( D )</td>
<td>0.008 puMW/Hz</td>
</tr>
<tr>
<td>Governor time constant, ( T_g )</td>
<td>0.10 s</td>
</tr>
<tr>
<td>Time constant, ( T_e )</td>
<td>0.25 s</td>
</tr>
<tr>
<td>Time constant, ( T_i )</td>
<td>8.0 s</td>
</tr>
<tr>
<td>Speed regulation, ( R )</td>
<td>2.5 Hz/puMW</td>
</tr>
<tr>
<td>Parameters of PV module</td>
<td></td>
</tr>
<tr>
<td>Rated output power</td>
<td>216 W</td>
</tr>
<tr>
<td>Open circuit voltage, ( V_{oc} )</td>
<td>36.50 V</td>
</tr>
<tr>
<td>Short circuit current, ( I_{sc} )</td>
<td>8.10 A</td>
</tr>
<tr>
<td>Shunt resistance, ( R_s )</td>
<td>50 ( \Omega )</td>
</tr>
<tr>
<td>Series resistance, ( R_s )</td>
<td>5 ( \Omega )</td>
</tr>
<tr>
<td>Ideality factor, ( A )</td>
<td>1.450</td>
</tr>
<tr>
<td>Inverse Saturation Current, ( I_{z} )</td>
<td>3.6047e-07 A</td>
</tr>
<tr>
<td>S.C. current temperature constant, ( T )</td>
<td>1.73e-03 ( \text{A/}^\circ \text{K} )</td>
</tr>
<tr>
<td>Number of cells in series, ( N )</td>
<td>60</td>
</tr>
<tr>
<td>Dimension</td>
<td>0.75 m²</td>
</tr>
<tr>
<td>Parameters of PV array</td>
<td></td>
</tr>
<tr>
<td>Rated output power</td>
<td>225 kW</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>584 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>526.50 A</td>
</tr>
<tr>
<td>Number of modules in series</td>
<td>16</td>
</tr>
<tr>
<td>Number of modules in parallel</td>
<td>65</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>62,400</td>
</tr>
<tr>
<td>Parameters of Power converter</td>
<td></td>
</tr>
<tr>
<td>Inverter power rating</td>
<td>225 kW</td>
</tr>
<tr>
<td>Nominal ac output voltage</td>
<td>480 V (3-p)</td>
</tr>
<tr>
<td>Nominal ac output frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Maximum ac line current</td>
<td>271 rms</td>
</tr>
<tr>
<td>Maximum dc input voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Maximum dc input current</td>
<td>781 A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>94.5%</td>
</tr>
</tbody>
</table>
by using an ESS. From the simulation results, it can be said that the PV-diesel hybrid system with the proposed method achieves flexible output power control, is effective in reducing frequency deviations significantly in comparison with fuzzy based frequency control, and delivers maximum PV power.

**APPENDIX**

**Minimal-order Observer**

The minimal-order observer described in (3) and (4) is manipulated in the following way as in [15] and [16].

A matrix $S$ of the form

$$
S = \begin{bmatrix} C \\ W \end{bmatrix} (n \times n)
$$

is derived for some matrix $W(n-l \times n)$, where $W$ has $n-l$ rows that are linearly independent of the rows of $C$. The matrices $A_{11}(l \times l)$, $A_{12}(n-l \times l)$, $A_{21}(l \times n-l)$, $A_{22}(n-l \times n-l)$, $B_1(m \times l)$, and $B_2(m \times n-l)$ are calculated by

$$
SAS^{-1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \quad \text{and} \quad SB = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}
$$

Then the parameters in (3) and (4) are obtained by

$$
\hat{A} = A_{22} - LA_{12} \quad (n-l \times n-l) \\
K = AL + A_{21} - LA_{11} \quad (n-l \times l) \\
\hat{B} = -LB_1 + B_2 \quad (n-l \times m) \\
D = S^{-1}\begin{bmatrix} 0 \\ I_{n-l} \end{bmatrix} \quad (n \times m) \\
H = S^{-1}\begin{bmatrix} I \end{bmatrix} \quad (n \times l)
$$

From Fig. 5, the state-space equation of the system can be obtained as

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4
\end{bmatrix} =
\begin{bmatrix}
-D/M & 0 & -1/M & 0 \\
0 & -1 & 1/T_d & 0 \\
0 & 0 & 1/T_g & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix} u
$$

$$
y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
x_4
\end{bmatrix}
$$

Now

**VI. CONCLUSION**

This paper presents a frequency control method for isolated power utility connected PV-diesel hybrid system. The proposed system increases or decreases system output power to respond to a high frequency or to a low frequency
\[
A = \begin{bmatrix}
-D & 1 & 0 & -1 \\
M & 1 & 0 & 0 \\
-1 & M & 1 & 0 \\
0 & Td & 1 & 0 \\
0 & 0 & Td & 0 \\
0 & 0 & 0 & Tg \\
\end{bmatrix} = \begin{bmatrix}
-1.2 & 10 & 0 & -10 \\
0 & -0.2 & 0 & 2 \\
0 & 0 & 10 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix},
\]

\[
B = \begin{bmatrix}
0 \\
0 \\
1 \\
Tg \\
0 \\
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
10 \\
0 \\
\end{bmatrix},
\]

and
\[
C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}.
\]

Therefore,
\[
S = \begin{bmatrix} 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \end{bmatrix},
\]

\[
SAS^{-1} = \begin{bmatrix} -1.2 & 10 & 0 & -10 \\
0 & -0.2 & 0 & 2 \\
0 & 0 & 10 & 0 \\
0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\
A_{21} & A_{22} \end{bmatrix},
\]

\[
SB = \begin{bmatrix} 0 \\
0 \\
10 \\
0 \end{bmatrix}^T = \begin{bmatrix} B_1 \\
B_2 \end{bmatrix}^T,
\]

\[
L = \begin{bmatrix} L_1 & L_2 & L_3 \end{bmatrix}^T,
\]

\[
\begin{bmatrix} sI - A \end{bmatrix} = (s - \gamma_1)(s - \gamma_2)(s - \gamma_3),
\]

where \(\gamma_1 = -8, \gamma_2 = 0.2, \) and \(\gamma_3 = -10,\) and

\[
L_1 = \frac{1}{10}(-\gamma_1 - \gamma_2 - \gamma_3 + 10L_3 - 10.2),
\]

\[
L_2 = \frac{1}{2}(\gamma_1\gamma_2 + \gamma_2\gamma_3 + \gamma_3\gamma_1) - 50L_1 + 51L_3 - 1,
\]

\[
L_3 = \frac{1}{20}(\gamma_1\gamma_2\gamma_3).
\]

Using the previous given values, parameters are obtained as

\[
\hat{A} = \begin{bmatrix} 1.75 & 0.2 & -1.95 \\
-9.75 & -10 & 9.75 \\
9 & 9 & -9 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \end{bmatrix}, \quad D = \begin{bmatrix} 0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \end{bmatrix},
\]

\[
H = \begin{bmatrix} 1 \\
-0.195 \\
0.975 \\
-0.9 \end{bmatrix}, \quad K = \begin{bmatrix} 1.3748 \\
15.4538 \\
5.265 \end{bmatrix}.
\]