Dynamic Modeling and Control of Renewable Energy Based Hybrid System for Large Band Wind Speed Variation


Abstract: This paper describes dynamic modeling and proportional-plus-integral (PI) controlled based frequency regulation of isolated autonomous hybrid system comprising of different renewable energy sources such as wind and photovoltaic (PV) with fuel cell (FC) and diesel engine generator (DEG) along with the energy storage elements such as flywheel energy storage system (FESS) and battery energy storage system (BESS). Large band wind speed based on Van der Hoven’s model and wind turbine dynamics is considered in this paper in order to analyze the frequency deviation. Ultracapacitor (UC) as an alternative energy storing element along with PI controllers has been considered in the hybrid systems in order to minimize the frequency deviation. A comparative assessment of frequency deviation for different hybrid systems in the presence of different storage system combinations reflect the improvements of the deviation in frequency profile in the presence of the ultracapacitors (UC) as compared to other storage elements.

Keywords: Frequency deviation, hybrid system, large band wind speed, PI controller, ultracapacitors.

I. INTRODUCTION

The energy crisis in the power sector has led to difficulties in meeting the increasing power demand. Distributed generation (DG) is increasingly being used to meet these energy requirements. DG uses small electric power generation systems located near consumers and load centers. Distributed generation provides reliable electric power and in addition, it also allows businesses to save on electricity costs by using their units during high peak demand periods when power is most expensive. This technology offers comparative advantages to large and centralized plants in terms of efficiency, reliability and security, low pollutions, transmission losses and capital investments. Growing DGs can improve the quality of atmosphere and reduce the green house effect. These technologies offer new market opportunities and enhanced industrial competitiveness.

In particular, advances in wind and PV generation technologies have increased their use in wind alone, PV-alone configurations. But the power outputs of wind and photovoltaic are unpredictable and fluctuating in nature due to large variations in wind speed and solar radiations. These characteristics may lead to unreliable and poor power supply. In this context, in order to overcome these difficulties, the renewable power generating systems can be integrated along with diesel engine generators (DEG) and different energy storage elements such as FESS, BESS to formulate hybrid renewable energy/storage systems such that power is uninterruptedly supplied to the load and simultaneously the minimum system cost can achieved [1]-[2]. Energy storage elements play an important role in hybrid energy system for storing and releasing energy according to the need. The sluggish response of FC can be eliminated by using it with flywheel energy storage system (FESS) or battery energy storage system (BESS) due to their high energy densities, high power exchange capability and high conversion efficiency [3]. But the intermittent nature of wind and photovoltaic causes mismatch in power generation and energy demand leading to deviation in frequency of the hybrid system which should be kept well within limit. Large band wind speed based on Van der Hoven’s model and wind turbine dynamics are considered in this paper in order to study the hybrid system performance. Further, in order to improve the frequency deviation, ultracapacitor (UC) as an alternative energy storage device and PI controllers are incorporated in the hybrid system. Ultracapacitors are an attractive choice as energy storage elements because of their advantages such as high efficiency, fast-load response, flexible and modular structure to be used with renewable sources such as wind and photovoltaic etc.

II. SYSTEM MODELING AND CONFIGURATION

The various renewable sources are integrated along with the energy storage elements to formulate three different topologies of hybrid systems as shown in Table 1.

<table>
<thead>
<tr>
<th>TOPOLOGY</th>
<th>ENERGY RESOURCES / STORAGE ELEMENTS</th>
</tr>
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<tbody>
<tr>
<td>HS1</td>
<td>2-WTG+1-AE+1-FC+1-DEG</td>
</tr>
<tr>
<td>HS2</td>
<td>2-WTG+1-DEG</td>
</tr>
<tr>
<td>HS3</td>
<td>2-WTG+1-AE+1-FC+1-PV+1-DEG</td>
</tr>
</tbody>
</table>

Fig. 1 Block diagram of Hybrid system (HS) 1

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Prior to the detailed study of the integrated hybrid system, the modeling and characteristics of the different components are carried out and presented in the subsequent sub-sections. Here in the modeling part, only the non-linearities of the wind turbine is taken into the modeling part but all other components in the hybrid system are simulated in simplified form as linear first order transfer functions in order to eliminate system complexities [4].

A. Large-Band Modeling Of Wind Speed

Starting from Van der Hoven’s model [5], we have developed a numerical wind speed simulation procedure, based on sampling the spectrum.

Let us consider, \( \omega_i, \; i = 1 \rightarrow (N + 1) \), the discrete angular frequency and \( S_{\nu_i}(\omega_i) \), the corresponding values of the power spectral density. The harmonic at frequency \( \omega_i \) has amplitude \( A_i \)

\[
A_i = \frac{2}{\pi} \sqrt{2 \left[ (S_{\nu_i}(\omega_i) + S_{\nu_i}(\omega_{i+1})) (\omega_{i+1} - \omega_i) \right]}
\]

(1)

and a phase, \( \phi_i \), which is randomly generated, with an uniform distribution in the domain \( [\pi, -\pi] \) [6]. The wind speed, \( \nu(t) \), is simulated with the relation

\[
\nu(t) = \sum_{i=0}^{N} A_i \cos(\omega_i t + \phi_i)
\]

(2)

\[9\]

Fig.2  Van der Hoven model based simulation of large band wind speed for a time of 300 s.

Fig.2 presents fluctuations in large band wind speed simulated based on Van der Hoven wind speed model over a period 300sec. The basic model of the turbulence component is given by the von Karman power spectrum [6]

\[
S_{\nu_i}(\omega) = \frac{0.475 \sigma^2}{(1 + (\omega L / \bar{V})^2)^{5/6}}
\]

(3)

where \( \sigma \) is the turbulence intensity, \( L \) is the turbulence length scales and \( \bar{V} \) is the mean speed .

In [6], the nonstationary turbulence component is modeled using a shaping filter with white noise input. The transfer function of the shaping filter is given by

\[
H_p(j\omega) = \frac{K_p}{(1 + j\omega T_p)^{5/6}}
\]

(4)

where the static gain \( K_p \) is obtained from the condition that the variance of the resulting colored noise \( \nu_x(t) \) is equal to 1. This condition is obtained with the following relation between parameters \( K_p \) and \( T_p \)

\[
K_p = \frac{2\pi}{B(\frac{1}{2}, \frac{1}{2})} \frac{T_p}{T_s}
\]

(5)

Where \( T_s \) is the sampling period and \( B \) designates the beta function and

\[
T_p = \frac{L}{\bar{V}_m}
\]

(6)

where: \( \bar{V}_m \) is the mean wind speed.

B. Non-linear modeling of Wind turbine power

The generated power of the wind turbine generator depends upon the variation in wind speed, \( \dot{V}_w \). The mechanical power output of the wind turbine can be expressed as a function of wind speed:

\[
P_W = \frac{1}{2} \rho A_r C_p V_w^3
\]

(7)

\( \rho \): The air density (kg/m\(^3\)); \( A_r \): The swept area of blade (m\(^2\)) and \( C_p \): Power co-efficient which is a function of tip speed ratio (\( \lambda \)) and blade pitch angle (\( \beta \))

The power output of wind turbine is relating to wind speed with a cubic ratio as given in (7). The power curve of the wind turbine is nonlinear as per the data given in Table 2 which is used for simulation and is taken from AIR 403 power curve [7, 8]. Both the first order moment of inertia (\( J \)) and a friction based dynamic model for the wind turbine rotor, and a first order model for the permanent magnet generator are adopted. The dynamics of the wind turbine due to its rotor inertia and generator are added by considering the wind turbine response as a second order slightly under-damped system [8], [11]. Using this simple approach, small wind turbine dynamic can be modeled as

\[
G_{wind}(s) = \frac{P_g}{P_{wr}} = \frac{0.25}{s^2 + 0.707s + 0.25}
\]

(8)

where \( P_g \) = power obtained from the power curve for a known wind speed & \( P_{wr} \) = actual output power of the wind turbine. The block diagram of the wind turbine with its non-linear transfer function is represented in Fig.3.
TABLE 2 WIND POWER AT DIFFERENT WIND SPEED

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Wind speed at sea level (m/s)</th>
<th>Output of wind turbine (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>120</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>220</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>330</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>520</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>710</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>800</td>
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<tr>
<td>12</td>
<td>20</td>
<td>125</td>
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<td>14</td>
<td>22</td>
<td>123</td>
</tr>
<tr>
<td>16</td>
<td>24</td>
<td>124</td>
</tr>
</tbody>
</table>

C. Modeling of PV, AE, FC & DEG

The transfer function of PV, AE, FC & DEG can be modeled as simple linear first order lag [4]. A part of \( P_{\text{WPG}} \) or/and \( P_{\text{PV}} \) is to be utilized by AE for the production of hydrogen to be used in fuel-cell for generation of power. Standby diesel engine generator (DEG) work autonomously to supply the deficit power to the hybrid system to meet the supply-load demand balance condition.

\[
G_{\text{PV}}(s) = \frac{K_{\text{PV}}}{1 + sT_{\text{PV}}} = \frac{\Delta P_{\text{PV},\text{PG}}}{\Delta \varphi} \quad (9)
\]

\( K_{\text{PV}} = \text{Gain Constant}=1.0; \ T_{\text{PV}} = \text{Time constant}=1.8\text{s} \)

\[
G_{\text{AE}}(s) = \frac{K_{\text{AE}}}{1 + sT_{\text{AE}}} \quad (10)
\]

\( K_{\text{AE}} = \text{Gain Constant}=0.002; \ T_{\text{AE}} = \text{Time constant}=0.5\text{s} \)

\[
G_{\text{FC}}(s) = \frac{K_{\text{FC}}}{1 + sT_{\text{FC}}} = \frac{\Delta P_{\text{FC}}}{\Delta \varphi} \quad (11)
\]

\( K_{\text{FC}} = \text{Gain Constant}=0.01; \ T_{\text{FC}} = \text{Time constant}=4.0\text{s} \)

\[
G_{\text{DEG}}(s) = \frac{K_{\text{DEG}}}{1 + sT_{\text{DEG}}} = \frac{\Delta P_{\text{DEG}}}{\Delta \varphi} \quad (12)
\]

\( K_{\text{DEG}} = \text{Gain Constant}=0.003; \ T_{\text{DEG}} = \text{Time constant}=2\text{s} \)

G. FESS/BESS as energy storage system

Flywheel Energy Storage System (FESS) stores energy in the form of the kinetic energy stored in the rotating flywheel and can be retrieved later as an electrical output. The advantages of flywheel systems versus batteries are higher power density, insensitivity to environmental conditions, no hazardous chemicals etc. Similarly Battery Energy Storage System (BESS) can be used for supplying power during peak load demand. The transfer functions of the storage systems FESS and BESS can be taken as first order lag [4].

\[
G_{\text{FESS}}(s) = \frac{K_{\text{FESS}}}{1 + sT_{\text{FESS}}} = \frac{\Delta P_{\text{FESS}}}{\Delta f} \quad (13)
\]

\[
G_{\text{BESS}}(s) = \frac{K_{\text{BESS}}}{1 + sT_{\text{BESS}}} = \frac{\Delta P_{\text{BESS}}}{\Delta f} \quad (14)
\]

\( K_{\text{FESS}}, K_{\text{BESS}} = \text{Gain Constants}=-0.01 \& -0.003 \)

\( T_{\text{FESS}}, T_{\text{BESS}} = \text{Time constants}=0.1\text{s each} \)

H. Ultracapacitors as alternative energy storage device

Ultracapacitors are electrochemical type capacitors which are used to store electrical energy during surplus generation and deliver high power within a short duration of time during the peak-load demand [9, 10]. Ultracapacitors possess a number of attractive properties like high efficiency, fast-load response, flexible, modular structure, longer life, no-maintenance and environmental friendly. The required amount of terminal voltage and energy or the capacitance of UC storage system can be achieved using multiple UCs in series and parallel.

Similarly the transfer function of the ultracapacitor can be represented as a first order lag:

\[
G_{\text{UC}}(s) = \frac{K_{\text{UC}}}{1 + sT_{\text{UC}}} = \frac{\Delta P_{\text{UC}}}{\Delta f} \quad (15)
\]

\( K_{\text{UC}} = \text{Gain constant}=0.7; \ T_{\text{UC}} = \text{Time constant of UC}=0.9\text{s} \)

I. PI Controller

PI type controllers are used before aquaelectrolyzer, fuel cell and diesel engine generators to minimize the mismatch in supply and power demand and hence the deviation in frequency profiles in the presence of different storage system combinations. The transfer function of a PI controller may be written as [11]

\[
G_{\text{PI}}(s) = \frac{K_{\text{P}}(1 + \frac{1}{T_{\text{I}}s})}{1 + sT_{\text{I}}} \quad (16)
\]

where \( K_{\text{P}} : \text{Proportional gain}; \ T_{\text{I}} : \text{Integral gain} \)

The value of the gain constant of aquaelectrolyzer \( K_{\text{ae}} \), fuel cell \( K_{\text{fc}} \) and diesel generator \( K_{\text{deg}} \) are taken as 50, 10 and 40 respectively on hit and trial basis.

TABLE 3 GAINS OF PI CONTROLLERS FOR EACH CASE

<table>
<thead>
<tr>
<th>Topology</th>
<th>Energy resources</th>
<th>Proportional Gain</th>
<th>Integral Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS 1</td>
<td>Aquaelectrolyzer</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Fuel cell</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>HS 2</td>
<td>Diesel generator</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Diesel generator</td>
<td>0.70</td>
<td>0.55</td>
</tr>
<tr>
<td>T HS 3</td>
<td>Aquaelectrolyzer</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Fuel cell</td>
<td>0.15</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Diesel generator</td>
<td>0.50</td>
<td>0.95</td>
</tr>
</tbody>
</table>
The optimal parameters of the PI controllers presented in Table 3 are determined by trial-and-error method such that the error in supply demand \( \Delta P_e \) is minimum. By controlling \( \Delta P_e \) and \( \Delta f \) we can supply high quality power to the connected load.

### J. Power and Frequency deviation

The power-frequency balance is maintained by a proper control of different power generation by the components. The power balance is achieved by the equation

\[
\Delta P_e = P_{H} - P_{L} \tag{17}
\]

where \( P_H \): Total Power generations ; \( P_L \): Total load demand

The change in the frequency profile (\( \Delta f \)) is expressed by the equation

\[
\Delta f = \frac{\Delta P_e}{K_{sys}} \tag{18}
\]

where \( K_{sys} \): the system frequency characteristic constant of the hybrid system. The transfer function for the system variation to per unit deviation in power is expressed by

\[
G_{sys} = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{sys} (1 + s T_{sys})} = \frac{1}{D + Ms} \tag{19}
\]

where \( M=0.4 \) and \( D=0.03 \) are respectively the equivalent inertia constant and damping constant of the hybrid system [4].

### III. SIMULATION RESULTS AND ANALYSIS

In this section the isolated hybrid systems comprising of different combinations of the generating and storage system combinations are simulated and analyzed for various operating conditions and disturbances. The hybrid systems with combination of energy storage elements like FESS-BESS and FESS-UC are simulated for analyzing the frequency deviations. All quantities in the plots of this section are in per unit (p.u.) values except that \( V_w \) is in m/s because of the random variation in wind speed. In the study, large band wind speed is generated based on the Van der Hoven spectral model and \( V_w \) is varied in a large band from 9 m/s to 21 m/s for a time period of 300s and the different cases of isolated hybrid systems are simulated for deviation in frequency profile during that period to know the system behavior and performances. The total power absorbed by the loads in the different hybrid systems is assumed to be 1.0 p.u. under normal operating condition. In order to study the frequency deviation, the hybrid systems are simulated considering non-linearities of wind turbines while all other generating and storage systems are assumed to be linear first order system. Parameters used in this study are taken from Dong Lee et al [4].

#### A. Time-domain simulation of isolated hybrid systems

Time-domain simulation of different isolated hybrid systems are obtained for a large band variation in wind speed and load disturbance as shown Fig. 2 & Fig. 4(a) respectively. The load demand is met by wind turbine generator, photovoltaic and fuel cell. In case of shortage, the deficit power required is supplied by the diesel engine generator. Aqua electrolyzer uses some portion of the wind turbine generator power output and produces hydrogen fuel for fuel cell. During surplus power generation, the extra power is stored in the energy storing elements which is supplied to the load in the period of power shortage. Fig. 4(a) shows the load profile and output powers of wind, DEG, AE, FC, FESS, BESS and UC respectively due to large band variation of the wind speed for HS 1.

1) During \( 0 \leq t \leq 50 \) s , the wind speed is varying randomly from around 9 m/s to 14 m/s and the load demand is 1 p.u. which is supplied by wind turbine generator, fuel cell and diesel engine. As there is no surplus power generation, so no energy is stored by the energy storing elements. The frequency deviation is almost zero in case of storage elements combination FESS-UC as compared to the combination FESS-BESS as shown in Fig. 4 (b).

2) For \( 50 \leq t \leq 100 \) s , the wind speed is varying from around 14 m/s to 21 m/s but the load demand is decreased to 0.5 p.u. , thus the wind power generation increases and DEG power decreases. The demand power is met by wind power generation, fuel cell and to some extent by the diesel engine generator. The frequency deviation is as shown in Fig. 4 (b) which shows the sudden increase and sudden decrease at 50 s and 100 s due to the sudden decrease and increase of load demand at the respective points.

3) During \( 100 \leq t \leq 150 \) s , the wind speed is varying from around 21 m/s to 13 m/s and the load demand is increased to 1 p.u..The demand is supplied by supplied by wind turbine generator, fuel cell and diesel engine generator. The frequency deviation is improved almost to zero in case of ultracapacitor as compared to the other storage elements.

4) Lastly for \( 100 \leq t \leq 150 \) s , the wind speed is varying from around 12 m/s to 15 m/s and the load is kept 1 p.u..The demand is supplied by supplied by wind turbine generator, fuel cell and diesel engine generator and the surplus power is stored in the storage elements. The simulation result reflects the improvements in frequency deviation in case of ultracapacitor as compared to the other storage elements.

Similarly the simulation results for output powers of wind, photovoltaic, DEG, AE, FC, FESS, BESS and UC as well as the comparison of the frequency deviation for the hybrid systems HS 2 & 3 is shown in Fig 5 and 6 (a) & (b) respectively. The comparative assessments clearly reflect that the frequency deviation is less with use of ultracapacitor under PI controller action in comparison to that of other storage elements combination.

#### B. Performance comparison of time-domain simulation results with and without PI controller

The comparative assessment of time-domain simulation results of HS 1, 2 & 3 with storage element...
combinations; FESS-BESS, FESS-UC without and with presence of PI controller is represented in Fig. 7, Fig. 8 and Fig. 9 respectively. This study confirms that when the load demands at the instants of 50 s & 100 s is decreased and increased suddenly, PI controller action helps to bring the frequency deviation nearly to zero effectively. It is observed from the simulation results that in the absence of PI controller, the frequency deviation exhibits more oscillations and does not track to the steady state quickly. But with the presence of PI controller it exhibits less oscillation and tracks to the steady state with minimum sample delay at the instants of sudden disturbance in load demand. The characteristics of ultracapacitors like high efficiency, fast-load response and higher energy density are exploited in this study to show better performance as compared to BESS. The simulation results clearly reflect the impact of ultracapacitors as energy storage element and PI controller towards the improvement in frequency deviation profile under load disturbance conditions and large band wind speed variations as comparison to other storage elements.
Fig. 6 (a) Power output of different components of HS3 (b) frequency deviation comparison in HS3

Fig. 7 Frequency deviation comparison in HS1 with and without PI controller for different storage element combinations

Fig. 8 Frequency deviation comparison in HS2 with and without PI controller for different storage element combinations

IV. CONCLUSION

The work presented in this paper has considered the study of frequency deviation in isolated hybrid renewable energy systems with different combination of energy storage elements in the presence and absence of PI controller. The dynamics of wind turbine is considered in modeling part to analyze the system performance. A comparative assessment of frequency deviations with the storage system combinations FESS-BESS and FESS-UC was being carried out with and without PI controller. A significant improvement in the deviation in frequency profile was observed in all cases of isolated hybrid systems in presence of PI controller and ultracapacitors as energy storage element as comparison to other combinations.

REFERENCES


