# Performance Study of Isolated Hybrid Power system with Multiple Generation and Energy Storage Units

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***Abstract*--This paper presents proportional-plus-integral (PI) controller based frequency regulation of isolated autonomous hybrid distributed generation system for sudden variation in load demand and wind. The developed hybrid system comprises of wind turbine generator (WTG), micro-turbine generator (MTG), fuel cell (FC), an aqua electrolyzer (AE) along with the energy storage device such as battery energy storage system (BESS). Further ultracapacitor (UC) as an alternative energy storage element is incorporated into the system for better performance. The generated hydrogen by an aqua electrolyzer is used as fuel for a fuel cell. The simulation results reported in the paper focused on frequency response for variable wind power, step load change and variable load.**

**Keywords-frequency deviation, hybrid system, energy storage unit, PI controller, ultracapacitor**

## I. INTRODUCTION

Our living environment has been severely polluted and destroyed due to consumption of large quantities of natural resources of the earth during the past several decades. Further, the impact of fossil fuel on the environment, especially the harmful effects of carbon emissions and the global warming have created a new demand for clean and sustainable energy sources. Several new forms of renewable resources such as wind power generation systems (WPGS) and photovoltaic systems (PV) to supplement fossil fuels have been developed and integrated globally. However, the photovoltaic generation has low energy conversion efficiency and very costly as compared to the wind power, wind assumes great importance and has the potential to make significant contribution. Wind power generator has the characteristic of fluctuating power output due to variation in wind speed. Therefore, due to sudden real power unbalance, the large frequency fluctuation occurs in such renewable energy hybrid small-scale local power system [1,5]. This paper focuses on the frequency stability of hybrid system and proposes a control means of combining wind power generator, MTG aimed to supply base load, electrolyzer system to produce hydrogen and a FC with energy storage elements is considered.

Microturbines have become the most promising distributed generator technology because of its performance of quick start, load following, voltage regulation, peak load shaving and black-start. Microturbines also offer the characteristics of low environmental impact, high reliability and excellent dynamic performance [2]. The MTG system can generate power in the range of 25kW to 500kW. In recent years, FC generation system has attracted a lot of attention due to its advantages as power generation system. The FC generation system offers many advantages over other power generation systems: diversity of fuel, high efficiency, low pollution, on-site installation and reusability of exhaust heat etc [3,4]. A FC is an electrochemical device that produces direct current electricity through the reaction of hydrogen and oxygen in the presence of an electrolyte. In order to absorb the rapidly fluctuating output power from wind turbine generator and generate hydrogen, aqua electrolyzer (AE) is used.

Several different concepts for hybrid distributed energy systems are currently under study and development. The proposed hybrid system in this paper consists of the integration of a high temperature FC and a MTG along with WPGS associated with available energy storage units. However, the output power of wind turbine generators is not constant and it varies with wind speed fluctuation. Further, this fluctuation results into frequency variation. In order to reduce the frequency deviation, the energy storage elements such as battery energy storage element and ultracapacitor and PI controllers are incorporated in the hybrid system which absorbs fluctuating power of wind turbine generators or load [6, 7, 8]. The energy storage elements play an important role in a hybrid system to store or release energy at an adequate time.

This paper is organized as follows: In Section II the system configuration is presented. Section III describes the modeling of various energy resources and storage systems in the form of transfer functions. Section IV presents analysis of time domain simulated results of the proposed hybrid system under various values of wind power and loading demand.

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Finally, based on the above study the conclusion is drawn in Section V.

## II. CONFIGURATION OF THE HYBRID SYSTEM

The configuration of the hybrid power generation and energy storage system is shown in Fig. 1. The system consists of WTG, MTG, FC, AE, BESS and UC. Aqua electrolyzer (AE) in Fig. 1 is used to absorb the rapidly fluctuating output power from WTG and generate hydrogen. The hydrogen is stored in the hydrogen tank and used as fuel for fuel cells. The power supplied to the load is the sum of output powers from wind turbine generator, micro-turbine generator, fuel cell, negative input power to aqua electrolyzer, the exchanged power of battery energy storage system and ultracapacitor. The expression for net power generation $P_H$ shown in Fig. 1 is given by

$$P_H = P_{WTG} + P_{MTG} + P_{FC} - P_{AE} \pm P_{BESS} \pm P_{UC} \qquad (1)$$

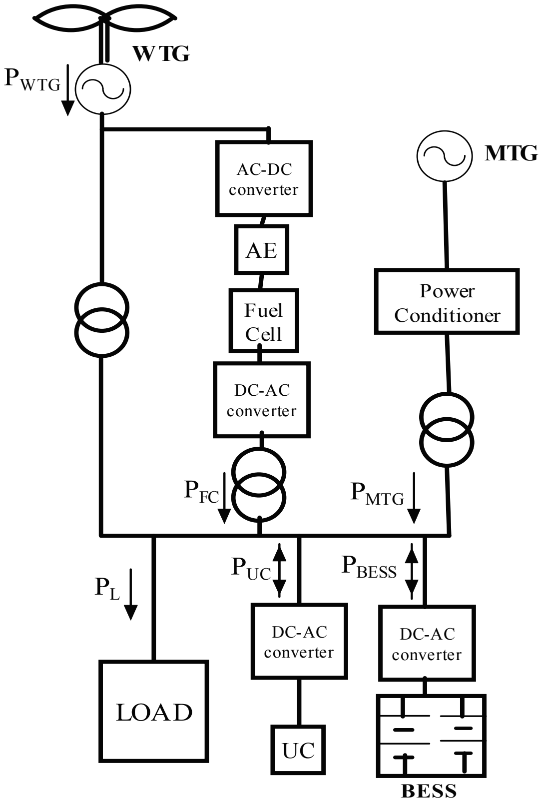


Fig. 1 Configuration of hybrid power generation/energy storage system

For large-scale power system simulations, simplified models or transfer functions are generally considered. In the present work, with the consideration of small disturbances like variable wind power, step load change and variable load, the system non-linearities have not been taken into account and the system is simulated in simplified form as linear first order transfer functions [9-11]. However, to precisely simulate the dynamic behaviors of practical WTG, MTG, AE, FC, BESS, UC, etc one should employ higher-order mathematical models with non-linearity. These higher-order mathematical models may include associated power conditioners and controllers.

## III. SYSTEM MODELING

The block diagram of the proposed hybrid system is shown in Fig. 2. The system consists of wind turbine generator, micro-turbine generator, fuel cell, AE, BESS and UC. The power supplied to the load is the sum of output powers from WTG, MTG, FC, AE and energy storing elements. The mathematical models with first order transfer functions for WTG, MTG, AE, FC and energy storing elements are given in this section.

### *A. Wind Turbine Generator*

The characteristic of wind turbine generator is illustrated in [9]. The output of WTG depends on the wind speed at that instant. The pitch system, which turns the pitch angle according to wind speed, introduces a non-linearity. The transfer function of the WTG is given by a simple linear first-order lag by neglecting the non-linearity [9]

$$G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{\Delta P_{WTG}}{\Delta P_W} \qquad (2)$$

Where $K_{WTG}$ and $T_{WTG}$ are the gain and time constant of wind turbine generator respectively.

### B. Micro- Turbine Generator

Considering the linear power frequency droop characteristic, the transfer function based formulation of a MTG which is normally supplying base load power is represented by the following equation [11,12].

$$G_{MTG}(s) = -\frac{1}{K_{MTG}} = \frac{\Delta P_{MTG}}{\Delta f} \qquad (3)$$

Where $\Delta P_{MTG}$ = Real time power fluctuation, $\Delta f$ = frequency fluctuation due to sudden fluctuation of real power, and $K_{MTG}$= droop property of micro- turbine output.

### C. Aqua electrolyzer and fuel cell

The transfer function model of aqua electrolyzer can be expressed by [9]

$$G_{AE}(s) = \frac{K_{AE}}{1 + sT_{AE}} \qquad (4)$$

Where $K_{AE}$ and $T_{AE}$ are the gain and time constant of the AE respectively. FC generator is a higher order model and has non-linearity. For low frequency domain analysis it is represented by a first-order lag transfer function model given as [9]

$$G_{FC}(s) = \frac{K_{FC}}{1 + sT_{FC}} = \frac{\Delta P_{FC}}{\Delta f} \qquad (5)$$

Where $K_{FC}$ and $T_{FC}$ represent the gain and time constant of fuel cell.

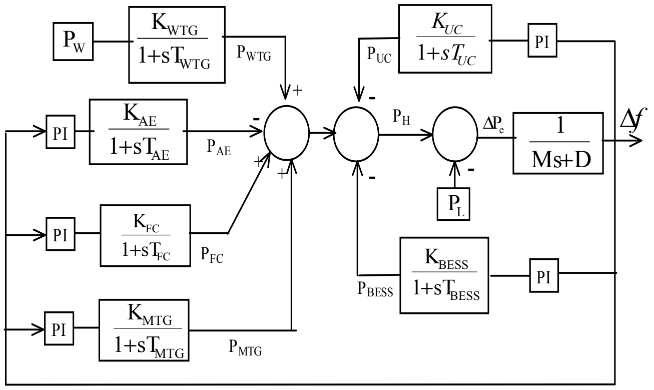
### *D. BESS/UC as energy storage system*

The transfer functions of the energy storage systems BESS and UC can be considered as first order lag [9,13].

$$G_{BESS}(s) = \frac{K_{BESS}}{1 + sT_{BESS}} = \frac{\Delta P_{BESS}}{\Delta f} \qquad (6)$$

$$G_{UC}(s)=\frac{K_{UC}}{1+sT_{UC}}=\frac{\Delta P_{UC}}{\Delta f} \qquad (7)$$

Where $K_{BESS}$ and $T_{BESS}$ represent the gain and time constant of BESS and $K_{UC}$ and $T_{UC}$ represent the gain and time constant of ultracapacitor. The employed parameters of the studied hybrid system [10,13] are listed in Table 1.



### E. Power deviation and system frequency variation

The total power generation must be effectively controlled to meet the total power demand of the connected loads in order to maintain a stable operation of an autonomous system. PI type controller is used before each power generation/energy storage system component to minimize the mismatch in supply and power demand and hence the deviation in frequency. The outputs of different system components are automatically adjusted by controlling the frequency deviation by PI controllers. The optimal parameters of the PI controllers presented in Table 1 are determined by trial and error method such that the error in supply demand ($\Delta P_e$) is minimum. The high quality of power can be supplied by controlling $\Delta P_e$ and $\Delta f$. Since system frequency is changed with net power variation, the system frequency variation $\Delta f$ is expressed by

$$\Delta f=\frac{P_H-P_L}{K_H}=\frac{\Delta P_e}{K_H} \qquad (8)$$

Where $P_H$ and $P_L$ are total power generation to the hybrid system and total load demand respectively. $K_H$ is system frequency characteristic constant of the hybrid power system. Since an inherent time delay exists between system frequency variation and power deviation, the transfer function for system to per unit power deviation can be expressed by

$$G_H(s)=\frac{\Delta f}{\Delta P_e}=\frac{1}{K_H(1+sT_H)}=\frac{1}{D+Ms} \qquad (9)$$

Where M=0.2 and D=0.012 are respectively the equivalent inertia constant and damping constant of the hybrid power generation/energy storage system [9, 10].

Table 1: Parameters of the hybrid system and PI controllers

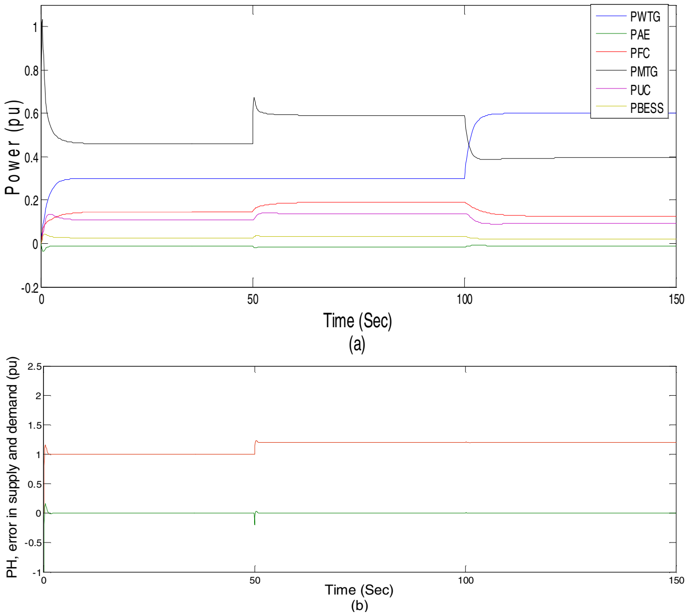
| Energy source/storage system | Gain Constant (K) | Time Constant (T) | Proportional gain | Integral gain |
|---|---|---|---|---|
| WTG | 1 | 1.5 | - | - |
| MTG | -20 | - | -0.1 | -0.3 |
| AE | 0.002 | 0.5 | -98 | -80 |
| FC | 0.01 | 4.0 | 89 | 92 |
| BESS | -0.003 | 0.1 | -10 | -90 |
| UC | -0.7 | 0.9 | -0.05 | -2 |

## IV. RESULTS AND DISCUSSIONS

In this section, time domain simulated responses of the proposed hybrid system using Matlab/Simulink under different operating points and disturbances are presented. The following three cases are considered for the study of frequency deviation due to variation of generated wind power and load fluctuation. A simulation interval of 150sec has been chosen.

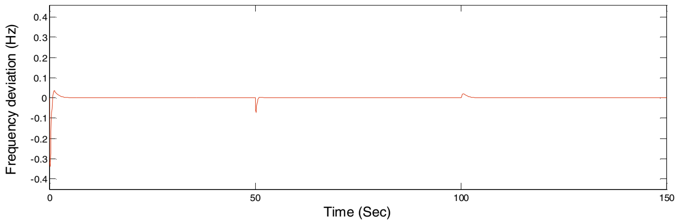
### *a. Time domain analysis: Case 1*

In this case, during 0 < t < 50 sec the load power $P_L$ is 1 pu and a 20% step increase in load occurs at t = 50 sec, also the wind power generated is 0.3 pu and suddenly increased to 0.6 pu at 100 sec. Due to sudden changes in load demand and wind power generation the frequency fluctuates. The outputs of different system components are automatically adjusted by controlling the frequency deviation by PI controllers. The optimal parameters of the PI controllers are determined by trial and error method such that the error in supply demand ($\Delta P_e$) is minimum. The frequency deviation is very close to zero since the total generated power just matches the required power demand of the connected load. Fig. 3 shows simulation results of $P_{MTG}$, $P_{WTG}$, $P_{FC}$, $P_{UC}$, $P_{BESS}$, $P_{AE}$, total power generation to the hybrid system $P_H$, error in supply and demand ($\Delta P_e$,) and frequency deviation $\Delta f$ for case 1.



(a)

(b)

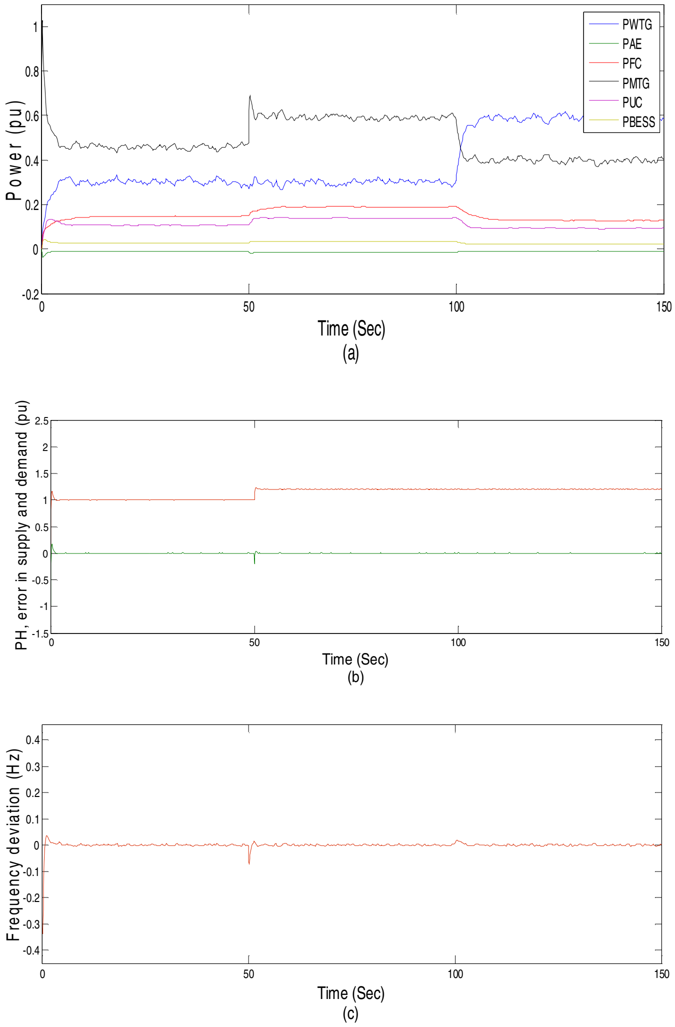


(c)

Fig. 3 (a) Powers associated with hybrid power generation/energy storage system (b) total power generation to the hybrid system $P_H$, error in supply and demand $\Delta P_e$ (c) frequency deviation $\Delta f$.

### *b. Time domain analysis: Case 2*

In this case, during $0 < t < 50$ sec the load power $P_L$ is 1.0 pu and a 20% step increase in load occurs at t = 50 sec. Also, the wind power generated is 0.3 pu up to 100 sec and beyond which it suddenly increases to 0.6 pu with random variation. Fig. 4 illustrates the time domain simulated results of case 2. The error in supply and demand ($\Delta P_e$) and also the frequency deviation $\Delta f$ are very close to zero.



(a)

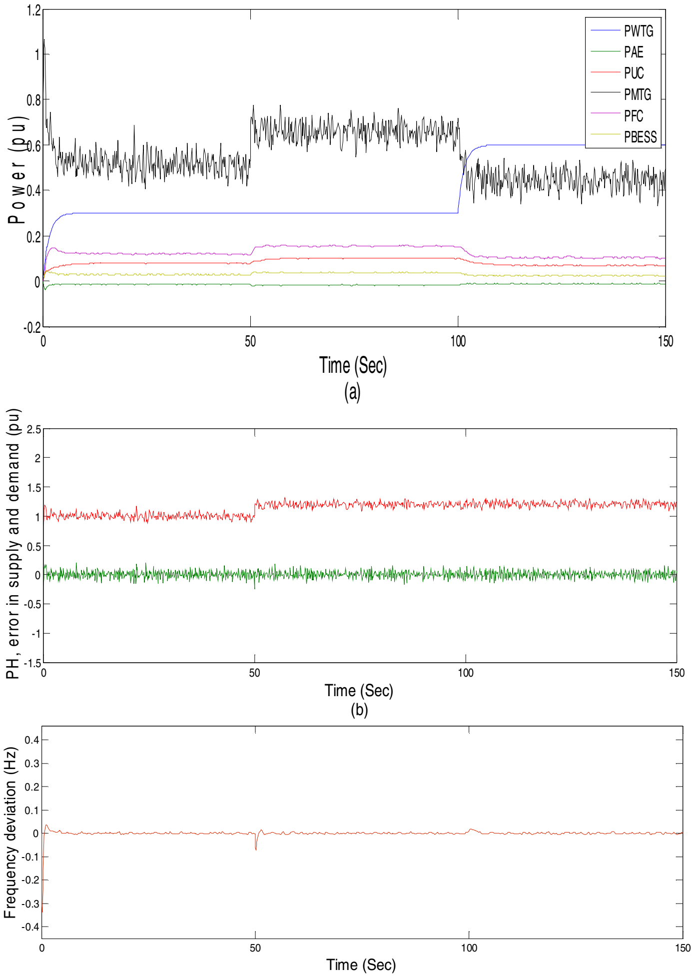
(b)

(c)

Fig. 4 (a) Powers associated with hybrid power generation/energy storage system (b) total power generation to the hybrid system $P_H$, error in supply and demand $\Delta P_e$ (c) frequency deviation $\Delta f$

### *c. Time domain analysis: Case 3*

For this case, during $0 < t < 50$ sec the load power $P_L$ is 1.0 pu and a 20% step increase in load occurs at t = 50 sec with random variation. The wind power generated is 0.3 pu up to 100 sec and suddenly increased to 0.6 pu at 100 sec. Fig. 5 illustrates the time domain simulated results of case 3. It can be clearly observed from Figs. 3, 4 and 5 that the system frequency deviation $\Delta f$ is also affected by the sudden or random power variation in wind power generation and load demand. By using PI controllers, the frequency deviation can be minimized by changing the generations of MTG, FC, power to aqua electrolyzer and power output of energy storage elements during changes in load or wind power generation or both. The frequency deviations for three cases are shown in Figs. 3(c), 4(c) and 5(c) respectively. It is found that, the deviation in frequency is suddenly decreasing at t = 50 sec and increasing at t = 100 sec due to sudden mismatch in supply and load demand. The frequency deviation is exhibiting less oscillation and comes back to steady state after few seconds by the proper tuning of the PI controllers.



(a)

(b)

(c)

Fig. 5 (a) Powers associated with hybrid power generation/energy storage system (b) total power generation to the hybrid system $P_H$, error in supply and demand $\Delta P_e$ (c) frequency deviation $\Delta f$

## V. CONCLUSION

The work presented in this paper has considered the study of frequency deviation in autonomous hybrid power generation/energy storage system with PI controller. The power system frequency deviates for the sudden changes in load and generation. It is found that when load is more than the power generated by the renewable source, the excess power requirement is supplied by other power generation/energy storage systems of the hybrid system. The hybrid system can supply high quality power using WTG, AE, FC generator and MTG along with energy storage units. It can be concluded from the simulated results of the three cases that the system frequency deviation can be properly controlled to be within a very small range.

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## VII. BIOGRAPHIES

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