FRACTIONAL-ORDER PID CONTROLLER DESIGN OF FREQUENCY DEVIATION IN A HYBRID RENEWABLE ENERGY GENERATION AND STORAGE SYSTEM

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ABSTRACT

In this paper, a fractional-order PID (FOPID) controller is implemented for frequency deviation control of a proposed hybrid fractional-order power generation and energy storage system. This control strategy is designed based on coordination control of fractional-order fuel cell and supercapacitor bank models in a hybrid renewable energy system with stand-alone application. The system performance is verified by using real weather data and under isolated loads in power frequency balance condition. Analyses show the validity of the control strategy in the proposed hybrid system and enhanced power quality.

INTRODUCTION

A stand-alone power system, also known as remote area power supply, is a grid independent system for locations that are interconnected to a weak grid or not fitted with an electricity distribution system. This hybrid system typically includes one or more methods of electricity generation, energy storage, and regulation [1].

Wind and photovoltaic power generation are two of the most attractive renewable technologies in the hybrid stand-alone power system in which have developed greatly in recent decades due to increasing concern on energy issues and rising environment warming and pollution [2]. In order to stabilize power supply and prevent power fluctuation of wind and solar resources due to weather condition variation and integrating purposes, some form of energy storage or additional generation such as battery and fuel cell (FC) is generally needed and incorporated into the system [3].

FC is an energy generation element that converts chemical energy into electricity and holds the promise of high efficiency and low pollution for applications including stationary electricity generation [4]. There are multiple types of FC technologies which although exhibit good power capability during steady-state operation, the dynamic response of FCs during transient and instantaneous peak power demands is relatively slow, and consequently, have different long duration of time delay [5]. Due to this reason the FC system cannot change its power to desire value, and is always associated with energy storage systems to improve system performance. DC-link capacitor as an auxiliary device cannot compensate the variation of load demand, and its voltage variation is not in allowable range for safe operation of inverters. So, supercapacitor, also named double-layer capacitor (DLC), a very fast power response flexible, modular structure and high power density, can compensate the variation of load demand and FC system power [6]. With proper control and effective coordination among various subsystems (FC and DLC), the power for the load demand can be effectively delivered and supplied by the hybrid power generation system [7]. Realistic modelling of these subsystems especially generation elements such as FCs and energy storage systems such as DLCs is crucial for future development of these hybrid sources [8].

Although Fractional calculus has a long history, its applications such as dynamical modelling and controller design are just a recent focus of interest in various fields of science especially physics and engineering [9]. Fractional modelling has more advantages and consistency than classical integer-order modelling and can provide an exact description of different phenomena. In many literatures fractional-order models of energy storage systems and generation elements have been introduced which provide best fit to experimentally measured impedances and/or transient responses and employ one or more constant phase elements (CPEs) [10]. The employment of fractional-order capacitors is imperative not only to the accuracy of the model but to reflect the physical electrochemical properties of the device. Furthermore, this realistic modelling of subsystems can efficiently improve the control purposes.

A number of studies have been reported to investigate modelling of hybrid renewable energy systems and frequency deviation control with different control strategies. The small signal stability analysis [11], frequency control with reduced dump load technique [12], output power control of wind turbine generator by pitch angle control [13] and frequency deviation control based on coordination of classical models of FC and capacitor [15] are parts of these activities.

In this paper, the FOPID controller is implemented for the proposed hybrid fractional-order power generation and energy storage system to control the frequency deviation. The control strategy is based on the coordination control between fractional-order FC (FOFC) and fractional-order DLC (FODLC) models in which compensates the shortage and complement whole hybrid power generation with considering the effects of system frequency variation. So, the load variation is reduced by FOFC and FODLC in low frequency domain and high frequency domain, respectively. The system performance is verified under isolated loads in power frequency balance condition by using real weather data. Analyses show the validity of the proposed control strategy for frequency deviation control and enhanced power quality.

HYBRID FRACTIONAL-ORDER POWER GENERATION/ENERGY STORAGE SYSTEM STRUCTURE

The generalized block diagram of the proposed stand-alone hybrid fractional-order power generation/energy storage system is illustrated in Fig. 1. The power generation subsystems include a wind turbine generator (WTG), a photovoltaic (PV), a fractional-order FC system (FOFC) and a fractional-order DLC (FODLC) bank is employed as energy storage system. All the four energy systems are connected in parallel to a common ac bus line to feed isolated loads in which PV, FOFC and FODLC are connected through three individual ac/dc converters. In the proposed system the renewable power generation subsystems PV and WTG are used as primary energy power generation, and have priority to produce power to satisfy load demand.

Renewable power generation systems with a combination of the FODLC, is suitable to stabilize power supply. In contrast, the proposed system is mainly composed of natural energy sources (wind power and solar power), and consequently, the FOFC is incorporated into the system as well. However, there is a tendency that the greater the system sophistication, the more suitable the power control techniques are required to be. To detailed study of the proposed system precisely and suitable design of control technique, accurate high order mathematical models with best fit to experimental data should be employed. Hereon, to simulate and investigate of such systems with this complexity, simplified linear fractional-order model are generally employed to FC and DLC. The mathematical models of the WTG, PV, FOFC and FODLC systems are presented in following sub-sections.

WTG model

The output power of WTG depends upon the wind speed. The extracted mechanical power P_{wind} (in *watts*) produced by WTG is given by [13]

$$P_{wind} = \frac{1}{2}\rho A \upsilon^3 C_p(\lambda,\theta) \quad (1)$$

where ρ is the air density (kg/m^3), A is the area swept by the rotor blades (m^2), and υ is the wind velocity (m/s), C_p is the rotor efficiency and is a function of tip speed ratio (λ) and pitch angle (θ).

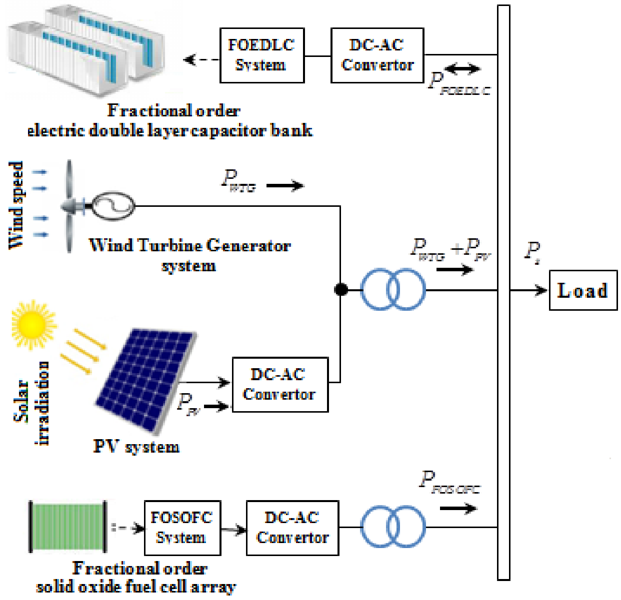


Fig. 1: Layout of proposed hybrid fractional-order power generation/energy storage system

The output power of the wind turbine can be regulated by pitch angle control. As indicated in Fig. 2, value of C_p can be changed by changing the pitch angle (θ), and the maximum rotor efficiency is obtained at a special λ, which depends on the aerodynamic design of a given turbine. Fig. 3 shows the output power of the WTG vs. wind speed. The output power maintained constant when wind speed is higher than the rated wind velocity even though the wind turbine has the potential to produce more power. This is done with the aim of the pitch angle control to protect the electrical system and to prevent the rotor from over speeding. When wind speed is greater than the cut out speed, the system is taken out of operation for safety of its components, and when wind speed is smaller than cut in speed, the output power of the WTG is zero.

The transfer functions of the linearized model of WTG shown in Fig. 1 is represented by a first order lag as [14]

$$G_{WTG}(s) = \frac{\Delta P_{WTG}}{\Delta P_{wind}} = \frac{1}{sT_{WTG}+1} \quad (2)$$

where T_{WTG} is the time constant of WTG system.

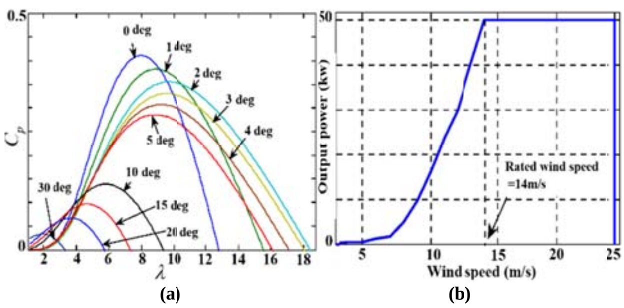


Fig. 2: (a) C_p - λ characteristics of the WTG at different pitch angles (b) WTG output power characteristic [13]

PV model

PV generation is a flexible and environmental friendly power generation method which its system consists of several photovoltaic generators connected in series and parallel to provide the desired voltage and current. The output power of the PV system can be express as follow [14]:

$$P_{PV} = \eta S \varphi \left(1 - 0.005\left(T_a - 25\right)\right) \tag{3}$$

where η is the conversion efficiency of PV array ($^\circ C^{-1}$), S is the measured area of PV array (m^2), φ is the solar irradiation (W/m^2), and T_a is the ambient temperature ($^\circ C$). The transfer function of the linearized model of PV can be represented by a simple first order lag as:

$$G_{PV}(s) = \frac{\Delta P_{PV}}{\Delta \varphi} = \frac{1}{sT_{PV} + 1} \tag{4}$$

where T_{PV} is the time constant of PV system.

FOFC model

There are multiple types of FC technologies that are being pursued that include proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), direct methanol fuel cells (DMFCs), and microbial fuel cells (MFCs). SOFCs have been considered as one of the most promising technologies for very high-efficiency electric energy generation from natural gas, both with simple FC plants and with integrated systems [15].

The fractional-order model of SOFC (FOSOFC) was presented in [16] to improve the control design purposes; which requires an accurate dynamic model. In this case, all the dynamic behaviors can be accurately captured by the proposed free fractional-orders elements. Compared to the classic integer-order equivalent circuit models in the literature, a fractional-order model has the advantage of higher modeling accuracy especially for the dynamic behavior under transient operation conditions.

The developed model of SOFC incorporates two CPEs to account for the behavior of the anode and cathode of the FC. The transfer function of the linearized FOSOFC model can be represented by

$$G_{FOFC}(s) = \frac{1}{s^{\alpha_1}T_1 + 1} + \frac{1}{s^{\alpha_2}T_2 + 1} \tag{5}$$

where T_1 and T_2 are the time constant of the electrical double layer of FOSOFC system, and s^{α_i} ($\alpha_i \in \mathbb{R}$; $i = 1, 2$) is the general frequency-domain from a circuit theory perspective.

FODLC model

Electric double-layer capacitors (EDLC), also referred to as Super-capacitors or ultra-capacitors, are electrical energy storage for wind turbines, renewable energy sources, hybrid and electric vehicles, biomedical sensors to wireless sensor nodes. Traditionally, these elements have been modeled using linear first order equations to describe their behavior over wide frequency bands [14], with larger frequency bands requiring a greater number of parameters. However, recent work has employed the concept of fractional-order model to describe the behavior of these components [17]. A simple fractional-order EDLC (FOEDLC) model derived from the porous electrode behavior of EDLCs given by

$$G_{FOEDLC}(s) = 1 + \frac{1}{s^{\beta}T_{EDLC}} \tag{6}$$

where T_{EDLC} is the time constant of FOEDLC system, and s^{β} is the general frequency-domain from a circuit theory perspective.

SYSTEM FREQUENCY VARIATION

The supply power must be effectively controlled to maintain a stable operation of an autonomous system since the output power of different power generation and components fluctuates under some conditions. The control strategy to satisfy power demand is based on the error in power balance ΔP which is defined as the power supply (P_S) minus the power demand (P_D) as follow:

$$\Delta P = P_S - P_D \tag{7}$$

In the proposed system, generating power varies, then the frequency fluctuates depending on variation of generating power. The frequency deviation Δf is expressed by the equation

$$\Delta f = \frac{\Delta P}{K} \tag{8}$$

where ΔP is the variation of generating power, and K is called system frequency characteristic constant of the hybrid power system. In actual practice, there will be a delay in the frequency characteristics and, hence, the above ideal equation is modified as

$$\Delta f = \frac{\Delta P}{K\left(sT + 1\right)} = \frac{\Delta P}{sM + D} \tag{9}$$

where T is the frequency characteristic time constant, D and M are the load damping and inertia constants, respectively.

CONTROL STRATEGY AND MODELING

For the control system, a generalization of the classical PID controller, namely the $PI^{\lambda}D^{\mu}$ or fractional-order *PID* (FOPID) controller is used in this paper [9]. This type of controllers involve an integrator of order λ and a differentiator of order μ. In frequency domain the $PI^{\alpha}D^{\mu}$ controller mathematically has the form

$$G_{FOPID} = k_p + \frac{k_i}{s^{\lambda}} + k_d s^{\mu} \tag{10}$$

The $PI^{\alpha}D^{\mu}$ controllers are installed on FOSOFC and FOEDLC, respectively, and these configurations are shown in Fig. 3. As seen, the supply power generation is comprised by power of WTG, PV, FOSOFC and FOEDLC system. The expression for given P_s by

$$P_s = P_{WTG} + P_{PV} + P_{FOFC} \pm P_{FODLC} \qquad (11)$$

In the proposed system, a high-pass filter (HPF) is used to reduce charging and discharging of FODLC bank in long-term. The frequency deviation of overall system divided in two parts with the aim of HPF. FODLC bank compensates high frequency deviation due to its fast respond and FC system compensates low frequency deviation.

SIMULATION RESULTS

To develop an overall power management strategy for the proposed system and to investigate the system performance, dynamic models for the main subsystems have been developed using MATLAB/Simulink. The employed parameters for modeling of system are listed in Table 1, and the real wind speed and solar irradiation is shown in Fig. 4a and Fig. 4b respectively.

Simulation results are shown in Figs. 5-8. Here, sampling time expresses the time scale used in analysis, and assumption time expresses the time on the representative day to be simulated. The sampling time interval was set to 5×10^{-5} in the case study in which this value corresponds to 0.003 min in the assumption time. Fig. 5a and Fig. 5b are the output power of WTG and PV systems, respectively. Fig. 6a and Fig. 6b are the output power of FOEDLC and FOSOFC systems, respectively. Steps load demands are applied to show the effectiveness of proposed control strategy as shown in Fig. 7. The Fig. 8 shows that the frequency deviation can be control appropriately using FOPID by coordination between FOSOFC and FOEDLC to compensate the shortage and to complement whole hybrid power generation with considering the effects of system frequency variation. Also, the result simulation of comparative study between PID and FOPID in proposed system is done based on two criteria transient and steady state responses. In term of transient response, FOPID has less oscillatory response (small overshoot) and almost less settling time with 2953 samples versus 3544 samples of PID which shows about 17% reduction for the first oscillation. This indicates that FOPID has faster transient time which approximately 1.2 times faster compared to the PID. In term of steady state, the FOPID has small steady state error about 50% less than the PID. Moreover, FOPID manage to reduce value of mean square error (MSE) from 1.66×10^{-7} to only 1.56×10^{-7} which is about 7% reduction from the PID for the whole day. This analyze of the simulation result indicate that the FOPID has the capability to improve transient performance and MSE value since the FOPID is more flexible (with five adjacent parameters) and gives an opportunity to better adjacent the dynamical properties of proposed fractional-order system.

Table 1: Parameters of the studied hybrid fractional-order system

$T_{WTG} = 1.5s$	$T_1 = 0.2s$, $T_2 = 0.2s$
$T_{PV} = 1.8s$	$T_{EDLC} = 0.1s$
$M = 0.4$, $D = 0.03$	$\alpha_1 = 0.8$, $\alpha_2 = 0.8$, $\beta = 0.5$

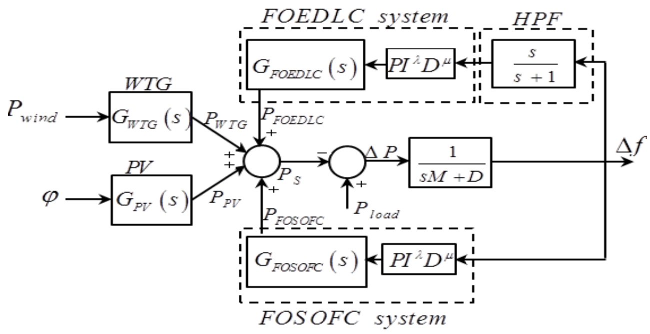
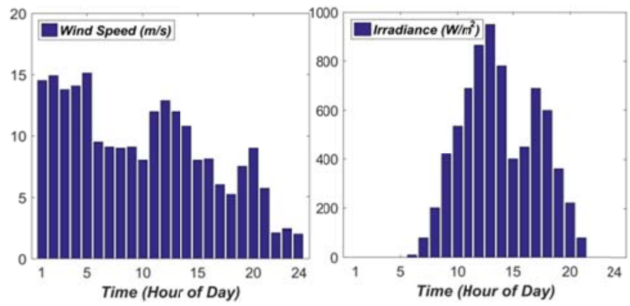
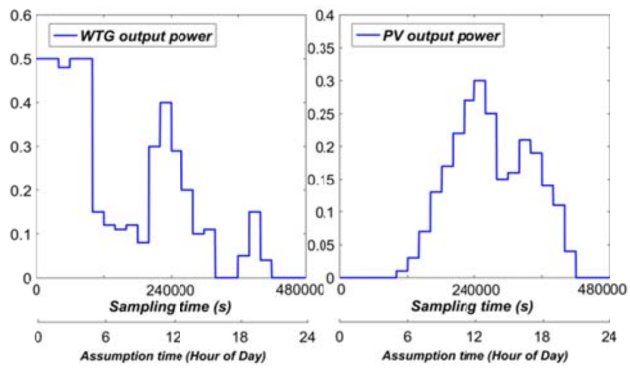


Fig. 3: (a) Real wind speed data (b) Real irradiance data



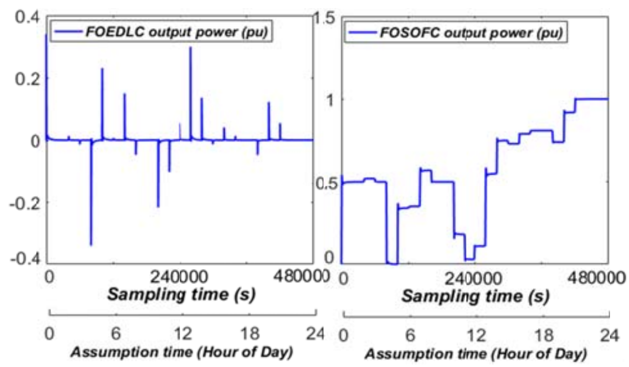
(a) (b)

Fig. 4: (a) Real wind speed data (b) Real irradiance data



(a) (b)

Fig. 5: (a) WTG output power (b) PV output power



(a) (b)

Fig. 6: (a) FOEDLC output power (b) FOSOFC output power

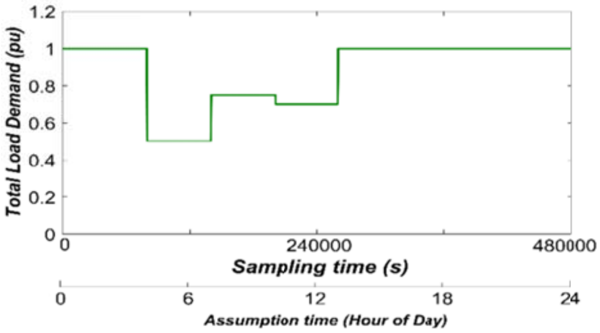


Fig. 7: Variation of load demand

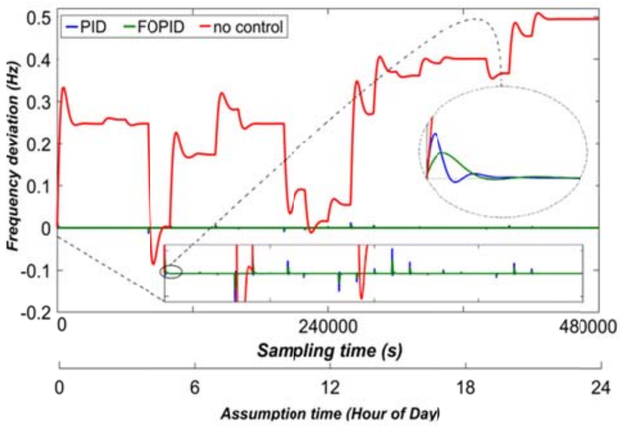


Fig. 8: Frequency deviation

CONCLUSIONS

In this paper, a fractional-order PID controller was implemented for frequency deviation control of a proposed hybrid fractional-order power generation and energy storage system based on coordination control between fractional-order models of fuel cell and supercapacitor bank. The system performance is verified under isolated loads in power frequency balance condition by using real weather data, and the analyses were compared with the classical PID controller. The system with FOPID exhibited good time domain response and MSE value as compared with the integer order PID.

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