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Robust H-infinity load frequency control in hybrid distributed generation system

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ABSTRACT

This paper presents a study on isolated hybrid distributed generation (DG) system for improving the frequency deviation profile. The hybrid DG system consists of wind turbine generator (WTG), diesel engine generator (DEG), aqua-electrolyzer (AE), fuel cell (FC) along with energy storage units. The frequency control problem is addressed for DG system connected with superconducting magnetic energy storage (SMES) or ultra-capacitor (UC). The particle swarm optimization (PSO) based loop shaping of H-infinity controller is used and compared with those obtained by genetic algorithm (GA) to minimize the frequency deviation. The frequency stabilizing performance is analyzed under different disturbances. Also, the controller robustness in terms of system parameter uncertainties is tested for changes in parameter up to ±30% from its nominal value. The results demonstrate minimum frequency deviation as achieved by proposed controller with use of UC in hybrid DG system.

1. Introduction

The deregulation of electricity markets worldwide brings new perspectives for small power generation known as distributed generation (DG). In the past few years, DG technologies have attracted in providing energy solutions to some customers that are more cost-effective, environmental friendly and provide better power quality or reliability over conventional power generation options. Though, DG comprises a relatively small fraction of the total capacity; however, the penetration level is expected to increase in future [1]. Among the renewable resources, wind energy and solar photovoltaic have gained popularity due to their inexhaustible environmental friendliness characteristic and fast development in the technology. Additionally, fuel cell (FC) also offers alternate energy resource; both electricity and heat to its customer. However, the intermittency in wind speed and solar radiation characteristics tend to serious operating problem, thereby stability of isolated DG system, which is already a weak system. As a matter of fact, these resources need to be integrated along with some storage systems to form hybrid system (HS) for improved performance and better co-ordination, thereby minimizing individual operating limitations [2]. Among the storage systems; battery energy storage system (BESS), flywheel energy storage system (FESS), superconducting magnetic energy storage (SMES), compressed air energy storage (CAES) are popularly being considered to store the surplus energy and supply the peak-load demand [3–5]. However, BESS suffers from the problems associated to low-discharge rate, increased time required for power flow reversal and maintenance requirements, while FESS suffers from low energy density. Similarly, SMES is not viable for low power (<100 kW) applications and requires continuous operation of liquid helium system. Again, CAES has low efficiency and adverse environment impact. Therefore, as an alternative storage, ultra-capacitor (UC) offers another option to smoothen strong and short-time power solicitations of DG system and meet load demand due to its fast power response, flexible and modular structure [6,7].

In fact, a reliable and stable operation of isolated hybrid renewable energy system is more complex, unlike those with grid connected. The fluctuations in both wind speed and solar radiation lead to mismatch between the power generation and load demand resulting into deviation in system frequency and voltage from the nominal value. These undue disturbances if allowed to exceed beyond the tolerance limit may lead to undesired performance and result into damage of the connected devices/equipments. Therefore in order to minimize the deviations, various research studies have been reported in literatures [8–16]. However, fewer studies have reported the impact of energy storage on system frequency deviation in renewable based DG scenario.

Integration of renewable energy resources and energy storage in HS is discussed in [8]. The authors [9] have discussed their study on PI controller based isolated HS consisting of wind, diesel engine generator (DEG), aqua-electrolyzer (AE) and FC. Several simulation

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case studies of such system including battery storage are presented. Recently, Ray et al. [10] have presented the problem of minimizing frequency deviation in HS that included BESS, FESS, SMES and UC. A comparison among these storage systems is reported. However, use of PI controller suffers from the heuristic variation of its gain which may cause undesired performance in terms of stability, overshoot, settling time, etc. In this context, considering the uncertainties in the system parameters, random load change and fluctuations in wind speed and solar radiation, robust control techniques like H-infinity based on linear matrix inequalities (LMI), loop shaping and H_∞ using droop characteristic have been thus discussed by some researchers [11–13]. But these methods were designed on heuristic basis. The use of SMES has been considered in the study associated to power balance in minimizing frequency deviation [13] and interaction between the HVDC system and turbine-generator shafts [14]. Recently, the authors [15] have proposed use of fuzzy controlled super-capacitor bank to improve load frequency deviations in an interconnected two area power system. The study is simulated for 0.01 pu load disturbance. Similarly, due to high potential of genetic algorithm (GA) for global optimization, its application with H-infinity controller is discussed in the literature recently [5]. However, GA may be computationally slower and get trap to a local solution in the presence of system uncertainties and parametric variation scenarios. Thus premature convergence of GA degrades its performance and reduces its search capability. Therefore, particle swarm optimization (PSO) technique can be used to provide better convergence and computationally faster performance. PSO has been found to be robust in solving continuous non-linear optimization problems. The SMES system is costlier and the super magnetic coil is very sensitive to temperature, current density and critical magnetic field, which creates stability problems when more resources are integrated in the system. In this context, the conventional wind–diesel system can be made more reliable by adding FC as an additional generating source along with alternate energy storage UC to compensate the slower response of FC.

This paper addresses the design of H-infinity loop shaping controller with gains being optimized by PSO, GA and H_∞ with droop control strategy. The comparative performance between these three controllers is presented. The effectiveness of controllers is tested to system uncertainties, stochastic variation in wind and random load demand. The normalized coprime factorization technique is applied to represent all unstructured uncertainties in the system. The performance and stability conditions in the H_∞ loop shaping method are applied in order to optimize the controller parameters by PSO and GA. Also, the potential application of SMES and UC in power balancing and thereby stabilization of weak hybrid DG system is addressed.

This paper is organized as follows; Section 2 describes the modeling of different energy resources, Section 3 describes the design of proposed controller, followed by integration of energy resources and storage units in Section 4. The time-domain and frequency-domain analysis based on simulation results under various operating conditions is given in Section 5. Finally, conclusions are drawn in Section 6.

2. Hybrid DG system modeling

The various energy resources; wind generator, diesel engine generator and fuel cell are integrated along with energy storage units to form a hybrid DG system. The intermittency in wind speed due to unpredictable variation may reduce the capacity of the energy storage units. Hence FC is integrated is such DG system along with the energy storage units like SMES and UC to overcome the stability related issues. In fact, the fuel cell–ultracapacitor (FC–UC) combination incorporated in the system compensates the slow dynamics of fuel cell. Besides, AE is connected to meet the availability of hydrogen production. The configuration of hybrid DG and energy storage units in study is shown in Fig. 1. In addition, H-infinity loop shaping controller based on GA and PSO are incorporated in the individual resources in order to control the respective power output and to obtain improved load frequency control in the hybrid system. Also, the design of H-infinity controller through droop characteristic is included in the study.

Prior to detailed study of integrated hybrid systems, the modeling and characteristics of the different components are carried out and presented in the subsequent sub-sections. In the modeling part, the system non-linearities and converters have not been taken into account and the systems are simulated in simplified form as linear first order transfer functions [8,10]. The block diagram of hybrid DG system in study is shown in Fig. 2. As shown, power is generated from wind generator, fuel cell and diesel engine generator is supplied to the connected load. A part (10%) of wind power generation is converted to hydrogen to be utilized as fuel input to fuel cell. When surplus power is generated from wind system, then it is stored in the storage unit SMES or UC. This power is later on used during the peak load demand. Therefore, the controllers in the form of PI, H-infinity droop, GA based H-infinity and PSO based H-infinity along with storage units SMES or UC are incorporated into the hybrid system in order to minimize the mismatch between the total power generation and load demand to keep the frequency deviation well within limit. The parameters and rating of the components of the hybrid system are given in Appendix A. A brief introduction of each energy resource is elaborated below.

2.1. Wind power generation

The output power of wind turbine generator depends on wind speed, V_W, varies as cubic function. The mechanical power output of the wind turbine is expressed as:

$$P_W = \frac{1}{2}\rho A_r C_p V_W^3 \tag{1}$$

ρ is the air density (kg/m^3); A_r the swept area of blade (m^2) and C_p is the power co-efficient which is a function of tip speed ratio (λ) and blade pitch angle (β). The different components of wind energy conversion system (WECS) and their models are given as first order lag [10], without any non-linearities:

$$G_{\mathrm{WTG}}(s) = \frac{K_{\mathrm{WTG}}}{1 + sT_{\mathrm{WTG}}} \tag{2}$$

where K_{WTG} is the gain constant; T_{WTG} is the time constant.

2.2. Super-conducting magnetic energy storage (SMES)

A SMES unit consists of a large superconducting coil at the cryogenic temperature. An SMES unit has the ability to follow system load changes almost instantaneously which provides for conventional generating units to operate at constant output. It has the capability to dampen out low frequency power oscillations and to stabilize system frequency as a result of system transients. The transfer functions of the storage systems FESS and BESS can be taken as first order lag:

$$G_{\mathrm{SMES}}(s) = \frac{K_{\mathrm{SMES}}}{1 + sT_{\mathrm{SMES}}} \tag{3}$$

where K_{SMES}, and T_{SMES} are gain and time constant of SMES.

2.3. Aqua-electrolyzer for production of hydrogen

A portion of wind power is utilized by AE for the production of hydrogen to be used in fuel cell. It may be expressed as first-order lag [8]: