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Frequency regulation in hybrid power systems using particle swarm optimization and linear matrix inequalities based robust controller design

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ABSTRACT

It is often necessary to investigate the output power against load demand in a system having distributed generation (DG) resources connected to the existing conventional power system. In this paper, the load frequency control (LFC) problem is presented using different optimization algorithms for two types of power system configurations: (i) hybrid configuration of thermal power system (TPS) integrated with DG, comprising wind turbine generators (WTGs), diesel engine generators (DEGs), fuel cells (FCs), aqua-electrolyzer (AE) and battery energy storage system (BESS); (ii) two area interconnected power system with DG connected in area-1. The inclusion of wind energy system in DG, having high variability in its output power, results into a challenging task for the realization of an effective controller design. This difficulty is further enhanced with random variation of load demand. The control scheme proposed in this paper is based on linear matrix inequalities (LMI) with its parameters tuned by particle swarm optimization (PSO), as a new contribution to earlier studies. The robustness of this controller is thoroughly demonstrated in the above hybrid power systems with different conditions of load disturbances, wind power and parameter variations.

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Introduction

The installation of distributed generation (DG) resources has being increased to meet the growing energy demand. In general, a DG system makes use of small electric power generation resources located nearby to its consumers and load centers. These generation resources include, among others, wind energy, diesel generator, fuel cells and energy storage systems. To meet the increased load demand of an isolated community, expansion of DG systems may be achieved through interconnection with conventional generation resources. The resulting hybrid power system intends to provide reliable and high quality service to its consumers, and this in turn depends mostly on the type and action of the controller implemented in the system.

Integration of DG resources especially based on wind turbines imposes new challenge to power systems control, making the electric power industry become more complicated.

In such hybrid system, deviations in load demand and stochastic variation in wind power adversely affect the frequency, so it is necessary to preserve the power balance between generation and demand, being achieved through automatic load frequency control (LFC) in some acceptable range. Compliance with frequency regulation policies set by regulation authorities becomes imperative. The frequency control issue in power systems having high penetration of wind systems is addressed in [1–3]. It is important to investigate the impact of high wind power penetration with conventional power flow in the overall area tie-line power. The wind system output power fluctuation dynamics has negative contribution to the power imbalance and thus to the frequency deviation, which should be taken into account in the existing LFC control scheme.

The control scheme implemented seems to be ineffective against wide the range of uncertainties in operation. In fact, frequency deviation in significant range may lead to under/over frequency relay trip and thus disconnection of system loads and generation. The study in this paper is related to the frequency regulation issue in hybrid power systems, with DG resources having negative impact on system frequency profile.

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Nomenclature

Δf	system frequency deviation (pu Hz)
ΔP_{WTG}	change in wind turbine power generation (pu MW)
ΔP_{WP}	change in available wind power (pu MW)
K_{WTG}	gain constant of the WTG
T_{WTG}	time constant of the WTG (s)
ΔP_{AE}	change in aqua electrolyzer power (pu MW)
K_{AE}	gain constant of the AE
T_{AE}	time constant of the AE (s)
ΔP_{FC}	change in FC power generation (pu MW)
K_{FC}	gain constant of the FC
T_{FC}	time constant of the FC (s)
ΔP_{DEG}	change in diesel power generation (pu MW)
K_{DEG}	gain constant of the diesel generator
T_{DEG}	time constant of the diesel generator (s)
ΔP_{BESS}	change in BESS power generation (pu MW)
K_{BESS}	gain constant of BESS
T_{BESS}	time constant of the BESS (s)
K_g	governor gain constant
T_g	governor time constant (s)
T_t	steam turbine constant
K_r	reheat gain constant
T_r	reheat time constant of the steam turbine
R	drooping characteristic (Hz/pu MW)
K_p	power system gain (Hz/pu MW)
T_p	power system time constant (s)
ΔX_E	small adjustment in position of governor valve (pu MW)
ΔP_t	small adjustment in thermal turbine thermal output (pu MW)

The different methods to tune gains of PI/PID controllers are given in [4,5]. A linear matrix inequalities (LMI) based linear quadratic regulator (LQR) control design for a wind farm is proposed in [6]. The design of robust PID controller using LMI approach is described in [7]. The application of H_∞ approach in controller design has played an important role in the study of numerous system dynamics since its original formulation. An integration of LMI and static output feedback represents a new approach in the design of PI/PID controllers. The LFC problem using LMI approach with consideration of time delay is also presented by some authors [8–11]. In [8] the authors described the LFC with communication delays using LMI approach. Bevrani and Hiyama [9] proposed a decentralized PI control approach with communication delays being considered as model uncertainty. Design of decentralized robust PI-based LFC for time-delay system is discussed in [10]. Frequency regulation for time-delay power system using LMI approach is described in [11].

The method for PI control design which uses a mixture of H_∞ control and genetic algorithm (GA) method to tune the gains of PI is proposed in [12]. Robust analysis and controller design for LFC is given in [13] and decentralized LFC for multi area power system is given in [14].

In the past, researchers have reported studies on LFC in a conventional system that consists of thermal/hydro or a combination of them using several variants of optimization techniques to design controller gains [15–20]. The performance of such design approach, however, depends not only on the optimization techniques, but also on the objective function. The authors of [18] have used bacteria foraging optimization technique for designing a frequency controller.

The scheme of LFC based on multi-objective GAs is described in [21]. The design of a robust decentralized controller for LFC of multi-area interconnected power systems is discussed in [22,23].

It is worth to mention that in the study considered here, an isolated DG system with conventional power system operates in a local region and is not wide spread over a large geographical region.

Thus, it becomes imperative to perform a study on the hybrid DG system. Further, the uncertainty of intermittent renewable energy resources with generation fluctuation may result in unintentional structure changes, which will further exaggerate the challenge for stabilizing the frequency response.

Recently, some authors [24–29] have reported their study analysing the influence of energy storage in frequency deviation considering renewable resources based DG system. A hybrid power system in an island for frequency control is described in [24]. Small-signal analysis of a hybrid renewable system with energy storage is discussed in [25–27]. The robust H_∞ LFC in hybrid systems is discussed in [28,29].

This paper explores, as a new contribution to earlier studies, the use of particle swarm optimization (PSO) and LMI – PSOLMI based controller design – to achieve minimum frequency deviation. The simulation results are demonstrated on two types of power system configurations. The first one is a hybrid configuration of thermal power system (TPS) integrated with DG, which comprises wind turbine generators (WTGs), diesel engine generators (DEGs), fuel cells (FCs), aqua-electrolyzer (AE) and battery energy storage system (BESS). The second configuration is a two area interconnected power system comprising of DG resources in area-1 with communication delay. The study investigates frequency deviation profile caused by a sudden change in generation and load demand in these two configurations. The robust control scheme via PSOLMI is tested under all possible disturbances, including the intermittent nature of wind speed and other uncertainties.

This paper is organized as follows; the optimization algorithms are given in 'Controller design algorithms', followed by the design strategy for two system configurations in 'Case study-1: hybrid power system' and 'Case study-2: two-area power system with DG', respectively. The simulation results are given in 'Results and discussion on case study-1' and 'Results and discussion on case study-2', and lastly the conclusions are provided in 'Conclusions'.

Controller design algorithms

This section describes an outline of various control designs via LMI approach.

H_∞ control design via LMI approach (H_∞)

The objective of H_∞ control theory is to design the control law u on the basis of measured variable y, so that the effect of disturbance w on control variable z_∞, given in terms of infinity norm of the transfer function from z_∞ to w, $\|T_{z_\infty w}\|$ does not surpass a specified limit γ demarcated as assuring robust performance. The classical closed-loop system through H_∞ robust control is represented as Fig. 1, in which $P(s)$ represents a linear-invariant system and $K_\infty(s)$ represents robust H_∞ controller [12].

State space representation of system model is given by:

$$\left.\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z_\infty &= C_1 x + D_{11} w + D_{12} u \\ y &= C_2 x + D_{12} w + D_{22} u \end{aligned}\right\} \tag{1}$$

where x is the state variable, w is the disturbance and other exterior input vector, u is the control input, z_∞ and $y$are controlled and measured output vectors, respectively.

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