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Load-following performance analysis of a microturbine for islanded and grid connected operation

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ABSTRACT

Modeling, simulation and performance analysis of a microturbine (MT) generator (MTG) system is carried out in this paper. The MTG system is consisting of a MT coupled with a synchronous generator. The proposed model incorporates power, speed and voltage controller for maintaining constant speed and voltage under variable loading condition. Modeling and simulation tasks are performed in MATLAB-SIMULINK platform for different loading conditions under isolated and grid connected modes. Performance study of the MTG system is carried out with and without both speed and voltage controller. It is observed from the simulation work that the MTG along with speed and voltage controller performs quite well under load disturbances, thereby, renders its suitability as a viable option for playing a key role as distributed generation for both isolated and grid connected mode of operation.

1. Introduction

Distributed generation (DG) system is going to play a key role in bridging the gap between the rate at which electrical energy demand is increasing and the generation capacity being added. A recent trend of decentralization in electric power utility is creating more opportunities for high penetration of DGs, serving as complimentary options to the centralized energy system. DG may be operated in dual mode with grid or without grid. Nevertheless, stand-alone DG systems are preferred more in hilly areas and remote villages where accessibility to the main grid is really a big challenge [1–3].

Apart from these, DGs are technically stable, economically feasible and environment friendly. These are small and efficient modular generation systems [4–6]. Recently, there is a growing concern among the researchers across the globe in developing microturbines (MTs) for DG applications owing to their quick start capability and easy controllability which may be useful for efficient peak shaving. Also, MTs render reliable and efficient operation along with lower maintenance cost and low greenhouse gas emission [7,8].

Microturbine generation (MTG) is a multi-fuelled generating system, incorporating simple cycle gas turbine technology with power generating capacity ranging between 25 and 500 kW. It suits best to meet peak load requirements of the consumer because of its quick start capability. Mainly, two types of MT are reported in the literature. One of them is very high speed, single-shaft MTG where generator and turbine are mounted on the same shaft while the other one is the split-shaft MTG system where a generator is connected via a gearbox to a power turbine [9–11]. Addition of DG affects the overall dynamics of the power distribution network, thereby, accurate modeling of MTG and its control have become inevitable to predict its grid and off-grid interaction in advance. Due to these reasons, researchers around the globe have been concentrating hard to explore accurate dynamic model of the MTG system.

Detailed theory of the gas turbine is well presented by Cohen et al. in [12]. In [9,13,14], modeling of single-shaft heavy duty gas turbine and its performance dynamics with acceleration, temperature and speed control are discussed. A review of different gas turbine model, developed till now, is presented and compared in [15,16]. So far as microgas turbine is concerned, its governing principle resembles heavy duty gas turbine theory. Modeling, simulation and control of load-following performance for grid/off-grid operations of MTG are well pursued in [17–21]. These works deal with single-shaft microturbine coupled with high speed permanent magnet synchronous generator (PMSG). High frequency electrical power generated by PMSG, eventually, cannot be used directly by the consumer. As a result, interfacing of power electronic devices between the MTG and the end user is inevitable. The usage of power electronic components results in conversion losses and makes the overall system operation and control more complex. To overcome these complexities while modeling of single-shaft MTG with power electronic components, split-shaft

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modeling of MT with either induction generator (IG) or synchronous generator (SG) is reported in [9,22–25]. The gas turbine governor model (GAST) developed by General Electric (GE) is the most commonly used model to study the dynamic performance of gas turbine. In [25,26], dynamics behavior of parallel operation of hybrid fuel cell and MTG system forming a microgrid is explored. Authors of [8,23,24,27] have used the GAST model for different load-following performance studies of split-shaft MTG system under with or without grid connected mode of operation. Sisworahardjo et al. in [24] have made a comparison between controller based on artificial neural network and conventional PI controller for standalone MT power plants. Oguz et al. have made similar type of approach in [27].

In the present work, GAST model of a split-shaft MTG is considered and simulated in MATLAB-SIMULINK® platform [28]. Slow dynamics of electro-mechanical system of a MTG is explored considering different load scenarios for islanding as well as grid connected mode of operation. Along with active power controller and speed controller, an additional voltage controller is also incorporated in the present work for load-following performance study of the proposed MTG system.

The rest of the paper is organized as follows. In Section 2, model of split-shaft MT along with its control mechanism is presented. The parameters used in the studied MT model are illustrated in Section 3. Simulation results are presented and discussed in Sections 4. Finally, conclusions of the present work are drawn in Section 5.

2. Split-shaft MT model

Most of the MTs use a single-shaft design configuration in which shaft rotates both the inlet air compressor and the generator. Single-shaft models are designed to operate at higher speed, typically, in the range of 50,000–120,000 rpm. These systems generate high-frequency alternating current (AC) which is rectified to direct current and, finally, inverted to 50–60 Hz AC using power electronic interface system [17–21]. Single-shaft MTs are incorporated with mainly three primary controllers viz. speed controller, temperature controller and acceleration controller. Each of these controllers modulates fuel control block and overall turbine dynamics, as and when required. Speed controller (being the primary controller) acts owing to the mismatch between reference speed and actual rotor speed. Temperature controller monitors the upper limit of the output power generated. Acceleration controller acts mainly to regulate the rate of acceleration of rotor during start-up [23].

On the other hand, twin-shaft MTs use two turbines. One is used to drive the air compressor while the other is used to drive the generator via a gear box. Exhaust coming out from the compressor turbine powers the generator turbine as shown in Fig. 1. The gear box is used to reduce the speed to 3600 rpm. With the pressure ratio splited between the two turbines, the lower output shaft speed of the second stage turbine is more conducive to directly accommodate a conventional generator such as an IG or a SG without any requirement of power electronic interface [29]. A recuperator and a waste heat recovery or a heat exchanger is incorporated to enhance overall efficiency and power generation output. The recuperator captures thermal energy of the exhaust from the power turbine for preheating compressed air whereas heat exchanger captures the exhaust energy to meet the heating load requirement of the consumers, if any. [8,22–27].

In this paper, a twin-shaft model of MT is used. As main focus of the present work is to explore the slow dynamics of the electro-mechanical systems under normal operating condition, recuperator and the heat exchanger (both being only system efficiency raising components) are omitted from the proposed model. For simplicity, actual temperature control which uses thermocouple for sensing exhaust temperature and acceleration control blocks are neglected in our studied model. It may be noted here that the temperature and acceleration control blocks do not participate under normal operating condition. In the present work, a speed controller is used in place of governor of MT system [23].

2.1. Split-shaft MT and its control

In the present work, the most commonly used GAST model of the MT (developed by GE) is simulated to study the load-following behavior. SIMULINK-based GAST model of MT with speed controller and active power controller is shown in Fig. 2. The parameter details of the MT model may be found in [23] and are listed in Table 1. As shown in Fig. 2, speed control is realized by incorporating a conventional proportional-integral (PI) controller which is used to control the error between reference speed (ω_{ref}) and the actual speed ω_{act} of the rotor. Similarly, from Fig. 2, it may be observed that the mechanical power output from the turbine (which in turn governs active power output from generator) is controlled by an another PI controller. The input to this PI controller is the difference between reference active power (P_{ref}) and the actual active power generated (P_{act}). The outputs of the speed controller (x_1), active power controller (x_2) and temperature control block (x_3) are given as inputs to a low value gate (LVG) which in turn governs the convenient fuel flow rate. Output of the LVG is given to fuel opening valve (FOV) block, represented by a first order transfer function (having time constant T_1) with maximum and minimum valve opening limits denoted by FOV_{max} and FOV_{min}, respectively. Depending upon LVG output, FOV actuates the fuel system block (having fuel system control time constant of T_2) to produce required fuel flow rate. Exhaust temperature block is represented by a first order time constant block with load limit time constant shown as T_3. The values of load limit (L_{max}) and FOV_{max} are taken as 1.2 (assuming that MT has 120% peak power capacity).

2.2. Simplified SG model and its control

A simplified SG model, as given in [23], is used for the simulation work of the present paper. In the present work, a predefined SG model (as available in SimPowerSystems toolbox of MATLAB™ [28]) is used which models both the electrical and mechanical characteristics of the SG. The parameters of the studied SG model are mentioned in Table 2. The real power output of the generator is controlled by a PI controller. In the present work, terminal voltage of the MTG system is maintained at desired level by using a voltage regulator whose input is the output of an another PI controller. This voltage control mechanism, in islanded mode, is beyond the scope of the work reported by Saha et al. in [23]. But this voltage control mechanism, in islanded mode, is considered in the present work. Input to the PI controller used in voltage control mechanism is the mismatch between reference voltage (V_{ref}) and the actual terminal voltage per phase (V_{phase}).

These controllers must work in unison to achieve two important targets viz. (a) meeting the power requirement at the consumer end and (b) keeping both the terminal voltage and the speed deviation (i.e. frequency) within their prescribed limits. A high quality power is expected from the MTG system when these two targets are fulfilled. The block diagram of the MTG system interconnected with the utility grid is shown in Fig. 3. A 150 kVA, 440 V, 60 Hz MTG system is interconnected with the utility grid via a 200 kVA, 11 kV/440 V, 60 Hz, Y–Δ transformer. The utility grid is modeled as a simple RL equivalent source with short circuit level 500 kVA with a load of 5 kW [23]. The off-grid and grid connected operation of the system may be realized by opening or closing of the circuit breaker located at the point of common coupling (PCC).