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Hybrid system with micro gas turbine and PV (photovoltaic) plant: Guidelines for sizing and management strategies

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A B S T R A C T

This paper presents a hybrid system consisting of a 100 kWe micro gas turbine (MGT) that juxtaposes the energy production of a photovoltaic (PV) plant whose yearly yield is available by on field measurements. The aim of the work is to model and investigate the behavior and the performance of a hybrid MGT-PV system under the topical constraint of firming renewable power and hence of guaranteeing a reliable power production to the grid. We propose a solution for the sizing of the PV plant and two strategies for the management of the hybrid system in order to guarantee a reliable day-ahead hourly forecast of the electric power that can be actually produced by the plant under whatever ambient condition. The results ascertain the advantages of the upgraded system in terms of natural gas consumption (−16%) and and NO_X (~ −33%) with a higher local emission of CO. In particular, the proposed hybrid system: i) solves the problem due to the unpredictability of PV energy production; ii) grants a significant reduction of the primary fuel usage and specific energy cost; but iii) increases the level of local pollutants, since it internalizes the emissions previously generated in a centralized power plant to produce the amount of electricity of the hybrid system.

1. Introduction

In the transition from the existing grid to the future smart grids the higher penetration of renewable energies [1] could arise concerns about the stability and operation of the electric grid which is not designed to deal with the intermittent and variable nature of renewable, particularly wind and solar, resources. According to Wang et al. [2] capacity firming is fundamental "to address the issues of load profile following and power balancing, capacity firming to reduce renewables' variable output". California ISO (CAISO) conducted a study [3] on issues related to the integration of renewable energy and found that accurate forecasts (both day-ahead and hour-ahead) of renewable energy production are fundamental both for reliable operation of the grid and for scheduling the energy production of other power plants. The issue of accurate forecasts of renewable energy generation was also addressed by Silva et al. [4] who proposed a methodology for distributed energy resource scheduling in smart grids, considering day ahead, hour ahead and 5 min ahead scheduling.

In this context, according to Chowdhury et al. [5], "microturbines are widely popular as generating units in distributed generation (DG) systems and as energy producers in CHP systems. At present they hold maximum prospect to be used as microsources for Microgrids." With an electrical power output ranging from 25 kW to 500 kW, Microturbines (MGTs) are a relatively new technology that is currently attracting a lot of interest in DG market [6–9]. The DG concept, recently in expansion as a result of deregulation of electric market, consists in using generators sized from few kWs to MW geographically distributed instead of using traditional centralized generation units sized from 100 MW to GW [10]. In the future probably the DG will be based strongly on renewable sources but, the short-term solution in the path to the diffusion of this scenario seems to be the use of hybrid generation sets consisting of a mix of renewable and conventional sources, and an energy storage system. As backup source for integrating renewable energy sources in hybrid systems, apart from MGTs, reciprocating engines (ICE) and fuel cells (FC) have been proposed [11–14]. FCs are probably the most promising technology but they are still too costly and less reliable with

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respect to the others. MGTs are generally preferred to ICEs [15,16], even if they are less efficient in generating electricity, thanks to their high power density, low environmental impact in terms of pollutants, low operation and maintenance (O&M) costs and multi fuel capability [17]. Depending on parameters such as grid availability, cost of grid supplied electricity, and meteorological conditions in the application site, DG hybrid systems can be either in stand-alone or in grid-parallel configuration. In particular, DG using MGTs is a typical solution for standalone, on site applications remote from power grids. Other applications are devoted to combined heat and power generation (CHP), peak shaving, standby power generation, reliability increase, power boost capacity, cost of energy decrease, and pollutant emission reduction [9]. As renewable energy systems have an unpredictable nature and dependence on weather and climatic conditions, their design must be optimal in terms of operation and component selection in order to obtain electricity reliably [18–20] and at a competitive price [21] from a hybrid system. For a given location, the optimum sizing of each component requires a detailed analysis of various site-dependent variables such as solar radiation, wind speed, ambient temperature and their influence on the performance of the components of the system. When optimum sizing has been achieved attention has to be paid to the dynamic behavior of the system in order to assure power quality, without voltage unbalance and voltage fluctuations [16,22,23]. To this respect, a concern in using MGTs in hybrid systems is their sensitivity to ambient conditions. Thus the knowledge of the effects of ambient conditions on the MGT performance is a key subject both for the sizing of the energy system and for its optimal dynamic control. Actually, when weather rapidly changes, assuring good power quality from a local grid consisting of photovoltaic panels or/and wind turbines aided by MGTs is a non-trivial problem. In general, the photovoltaic system is characterized by a production curve that is proportional to the availability of the solar radiation; the power production has a bell trend in a sunny day, with a maximum that is positioned in the central hours of the day. On the other hand, an MGT has a power production curve that depends on three variables (temperature, pressure, relative humidity) and shows an antithetical trend to that of the photovoltaic systems; this occurs because the parameter that has relatively more influence on the performance of the machine is the ambient temperature (the higher the temperature, the lower the maximum power production). Temperature, as well as solar radiation, usually has a maximum in the central hours of the day and, accordingly, the performance of the MGT have a deterioration. For this reason, coupling an MGT with a PV system seems to be an interesting solution for their integrating production profiles. Also in a paper by Ismail et al. [24] the MGT-PV coupling was proposed for a case study in Palestine. The authors provide an interesting evaluation of the advantages of this coupling and also supply an optimization procedure for the PV system design in order to minimize the energy production cost and the CO_2 emissions for a typical Palestinian rural community. Nevertheless, the effect of the ambient parameters on the MGT performance is not considered and a battery storage system is embedded to shave the energy production/demand surplus. The sensitivity to ambient conditions of the MGT, mainly ambient temperature, was deeply investigated by some of the authors of the present paper [25–28] and also techniques to reduce this detrimental impact have been studied [29,30].

In this work we took the advantage of the knowledge of a Turbec-T100 micro gas turbine in order to model and investigate the behavior and performance of a hybrid MGT-PV system with the constrain of an accurate day-ahead production forecasts which is essential for reliable operation of the power grid. In particular, we assess the implicit and topical constraint of firming solar power generation and hence of guaranteeing a reliable power production to the grid. Because of the uncertainty of the prediction of the PV plant production [31,32], the MGT must be able to offset rapid output changes of PV plant due to clouds to guarantee a reliable day-ahead hourly forecast of the electric power that can be actually produced by the plant under whatever ambient condition. The system was thought as an electric energy production device integrated in local low voltage distribution grid and not as an off-grid device that continuously follows a specific energy demand; therefore, no electric energy storage is required.

The first part of the paper presents the components of the hybrid system, its sizing and its management strategies in order to guarantee, for every hour of the following day, a reliable amount of power supply to the grid. The second part of the paper presents the results of the yearly output of the hybrid-system in terms of natural gas consumption, CO and NO_X emissions and mean specific consumption of the MGT depending on the size of the PV plant. In our work, experimental PV plant performance data as well as all the ambient variables influencing the PV and the MGT operation were collected for a whole year of operation and taken into account to supply a more realistic scenario of the behavior of the hybrid plant.

2. Hybrid system: PV capacity firming and operational limits

The hybrid system proposed in this work results from the upgrading of an MGT with a solar PV system. In this section, a procedure is proposed for sizing the PV plant to juxtapose to the MGT and then some plant management criteria are discussed to guarantee a defined power output with one day advance.

The hybrid-plant sizing procedure starts with the choice of the MGT and then goes through the evaluation of the adequate size of the PV plant which can be easily adapted with steps of few hundreds of Watt by varying the number of panels.

The criteria to be taken into account for the plant sizing and management can be summarized in three points: i) guaranteeing a day-ahead-defined power to the grid in any ambient condition, ii) minimizing the fossil fuel consumption, and iii) dispatching to the grid all the available renewable energy output (no energy storage); conditions ii) and iii) imply the minimization of the fossil to renewable power ratio.

2.1. Plant sizing

Given a generic MGT, its actual power working range (P_{MGT_a}) lays between a minimum, (P_{MGT_min}, that guaranties stable operation of the machine), and a maximum (P_{MGT_max}) which depends on ambient temperature:

$$P_{MGT\_\min} \le P_{MGT\_a} \le P_{MGT\_\max}(T_{amb}) \quad (1)$$

Now consider the criteria from i) to iii):

- according to condition i) the actual power output of the hybrid plant (P_a), which is the sum of the actual power of PV (P_{PV_a}) and MGT (P_{MGT_a}), must be equal to that defined the day-ahead for the hybrid system (P_d) given by the sum of the productions of MGT (P_{MGT_d}) and the PV (P_{PV_d}) regardless the actual ambient conditions:

$$P_a = P_d \Leftrightarrow \quad P_{MGT\_a} + P_{PV\_a} = P_{MGT\_d} + P_{PV\_d} \quad (2)$$

- according to condition ii) the MGT has to be used only when strictly necessary. Thus the MGT start-up has to be scheduled only when solar power is available, and, when operating, its power contribute to the hybrid plant has to be minimized: