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Supercharged gas turbine combined cycle: An improvement in plant flexibility and efficiency

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ABSTRACT

This paper shows an innovative combined cycle solution that allows to increase the plant operational flexibility improving, at the same time, its global efficiency in part-load operation. In fact, nowadays, the necessity to maintain a high plant performance in prospect to fluctuating energy demand from electric grid has become a very critical problem in the energy sector. The solution here presented is characterized by a supercharged gas turbine, with an innovative control strategy, integrated in a conventional NGCC (natural gas combined cycle). This proposed solution, called SNGCC (supercharged conventional natural gas combined cycle), with an additional compressor stage upstream of the GT (gas turbine) cycle, has allowed to achieve, during part-load operation, significantly higher efficiency respect to conventional natural gas combined cycle. Consequently, also the possible operation range is extended.

1. Introduction

Nowadays the world of the power generation needs of new solutions that can guarantee a high flexibility operation in order to balance electrical supply and demand, while maintaining high energy efficiency conversion. In addition, the recent liberalization of the electricity markets, together with the rapid expansion of the utilization of RES (renewable energy sources), is emphasizing the need, on the European scale, of improving the flexibility of power generation systems. In particular in Ref. [1], through a complete overview on literature and data concerning scenarios characterized by intermittent supply, the additional costs for the power system stability due to an intermittent generation has been shown. Additionally, in Ref. [2] the role of renewable energy on the generation electricity market and its effect on the electricity price, in European Union, is deeply analyzed. In particular, the authors assert that RES technologies are characterized by having lower short term marginal cost than other conventional technologies. Therefore, their entrance in the electricity markets allows the reduction of the wholesale electricity prices because they displace technology based on nuclear and fossil fuel in a marginal position. Regarding the Italian thermoelectric sector, a significant efficiency drop of combined cycle plants can be observed in the last years basing on annual reporting of Terna (the Italian Transmission System Operator – TSO). NGCC (natural gas combined cycle) plants, in fact, with particular reference to the period 2008–2012, were managed to compensate the RES growth and, therefore, partly operated as fluctuating back-up power, with significant effects in terms of: relevant decrement of yearly operation hours, operative conditions increasingly far away those optimal due to prevalent functioning at part-load. Moreover, as known, step changes, continual modulation and both hot and cold starts of the plant negatively affect both specific consumptions and emissions (CO_2, NO_x) [3]. This phenomenon has an international relevance. Also [4], in fact, remarks as in the last years, annual operation data of combined cycles based on gas turbines differ to some extent from the design conditions. Aiming to improve the thermoeconomic design of these power plants [4], proposes a methodology to achieve, at design level regarding the determination of nominal conditions, their thermoeconomic optimizations taking into account the frequent off-design operation.

However greater flexibility and efficiency are needed. Fossil fuel power plants, in fact, in the next years, considering also the further increase of RES exploitation envisioned up to 20% share of the overall production, should increasingly shift their role from providing base-load power to supplying fluctuating back-up power to meet power demand and provide grid balance. Greater flexibility, nowadays, it is required also relative to new coal and nuclear power plants. The interaction between capacities of intermittent (i.e. wind or solar power) and non-intermittent production plants and their efficient dispatch are wide discussed in Refs. [5,6].

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Nomenclature

β_T	turbine expansion ratio (−)
β_K	compressor "K" pressure ratio (−)
CC	combined cycle (−)
GT	gas turbine (−)
HRSG	heat recovery steam generator (−)
IGV	inlet guide vane (−)
NGCC	natural gas combined cycle (−)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{w\_des}$	design value of water mass flow rate (kg/s)
$\dot{m}_{w\_off\_des}$	off-design value of water mass flow rate (kg/s)
P	pressure (bar)
RES	renewable energy sources (−)
SNGCC	supercharged natural gas combined cycle (−)
T	temperature (K)
T_{IT}	turbine inlet temperature (K)
U	overall heat transfer coefficient ($W/(m^2K)$)
W_{cc}	combined cycle power (MW)
WGT	gas turbine power (MW)
WST	steam turbine power (MW)
η_K	compressor isentropic efficiency (−)
η_T	turbine isentropic efficiency (−)

Specifically in Ref. [5] a model was developed to determine the optimal capacity of intermittent and non-intermittent production plants anticipating their efficient dispatch. The authors assert that to implement an optimal energy mix in a market economy, electricity prices should vary with the availability of the intermittent source of energy and consumers should react accordingly. But the authors show how this scenario is not financially feasible, concluding that an electricity industry with a large share of intermittent sources is not sustainable without some form of integration in production, either structural or financial. In Ref. [6], the authors focus on part load operation of an 80 MWe combined cycle power plant in order to discover and quantify possible savings accompanied by efficiency improvement working far from the nominal operating point. Specifically they consider the benefits on efficiency obtained from gas turbine inlet air preheating, and demonstrate as this advantage can be applied to every combined power plant operating mostly in the part load mode. Moreover, the solutions proposed should be suitable also for the retrofitting of older power stations, as indicated in Ref. [7]; therefore limited modifications and capital expenses should be needed for their implementation. In this context, only some results are available relative to a particular strategy management of combined cycles in part-load. Specifically, it consists mainly in gas turbine inlet air preheating operated together with further methodologies, such as condensate preheating by activation of the currently idle hot water section and change in steam condensing pressure regulation [8]. The simultaneous application of these methodologies results in more than a 2% decrease in the power plant's natural gas consumption. Furthermore, the optimization of combined cycle power plant in part load operation usually deal with strategies used to maintain the firing temperature in part load equal to full load operation. In technical literature is widely discussed as this condition can be achieved through limited reduction in gas turbine inlet air mass flow by varying the inlet guide vane position [9,10]. This strategy, however, moves the compressor efficiency and, consequently, the global plant efficiency far from its optimum operating conditions. Additionally, this strategy allows a reduction of GT (gas turbine) produced power only up to 85% of nominal load.

Relative to this scenario, this paper wants to contribute to further improvements of natural gas combined cycles, based on topper gas turbine, providing, respect to the state of the art, enhanced electric efficiency at part-load and for a wider load operation range. It also points out that, although the technical solution characterized by the installation of supercharged gas turbine combined cycle is generally known in technical literature, the plant partialization strategy, here presented, is a significant improvement respect to the state of art, thanks to its innovative optimization of the components functioning. Specifically, the results obtained in terms of efficiency enhancement in partial load and the load operation range constitute relevant advances and novelty respect to the current solutions discussed above.

Therefore, basing on the need to significantly improve the efficiency in part load operation of a conventional NGCC (natural gas combined cycle), an innovative plant configuration is here proposed. Specifically, a solution characterized by a supercharged gas turbine, with an innovative control strategy, integrated in a NGCC was analyzed. In this solution, called in the follow SNGCC (supercharged conventional natural gas combined cycle), part-load regulation is mainly produced, differently from usual GT regulation practices such as fuel-only control, IGV (inlet guide vane) control, compressor mass bleed [11,12], by largely varying the air mass flow rate at the GT inlet. It is realized by adding a free compressor upstream of the GT (gas turbine) cycle and through the development of an innovative regulation method of both compression and combustion processes. The use of an additional compressor allows to divide in two stages the entire compression process and to provide, at the inlet of main compressor, a sliding pressurization suitably regulated varying the part-load degree. In this way, as discussed in the following, the compressor directly fastened with the turbine shaft is operated close to its design point also in part-load, while, the auxiliary compressor, disconnected from the turbine shaft, varies the rotational speed aiming to efficiency maximization under its current operative conditions (air mass flow rate and pressure ratio). Moreover, as detailed below, the fuel mass flow rate is regulated to optimize the turbine functioning. Further considerations are indicated in the following for the bottomer steam cycle, globally allowing the achievement, respect to the conventional NGCC solution, of significantly higher electric efficiencies during the part-load operation.

The performance analysis for both design point and part-load operation of the conventional NGCC and the SNGCC was carried out through suitable 0-D models developed in Aspen Plus [13] environment. Details relative to these models are provided in Sections 2 and 3. The part-load analysis, presented in Section 4, was implemented taking into account the turbines and compressors performance characteristic and so, for each part-load case, corrected mass flow rate, isentropic efficiency, pressure ratio were recalculated. Moreover, in both cases a single pressure HRSG (heat recovery steam generator) was considered and the overall heat transfer coefficient U, with a fixed heat exchange area, was evaluated with a power law expression as detailed in Section 2. The main results, in terms of the enhanced performance of SNGCC system respect to conventional NGCC, are presented and discussed in Section 5 relative to the main parameters characteristic of both GT and steam sections.

2. Reference combined cycle (NGCC)

A conventional NGCC (natural gas combined cycle), shown in Fig. 1, was used as reference plant for the issues investigated in this study. Main components of NGCC are: gas turbine (compressor "K", "BURNER" and turbine "T"), HRSG ("heat recovery steam generator") and TSTEAM ("steam turbine"). In order to simplify the part-