A General Overview of Combined Cycle Gas Turbine Plants

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Abstract: The Combined Cycle Gas Turbines (CCGT) has encountered a large diffusion over the last decades. Different researchers have focused on performance evaluation of CCGT through mathematical modeling techniques. Hence, there are some important factors which should be respected while modeling the CCGT. These factors include type of different components of the CCGT system, their configuration, the modeling methods, and the purpose of the modeling, the type and structure of the control system and the simulation objectives. Hence, a brief overview about CCGT design and technologies, mathematical modeling, simulation tools and methods are presented in this paper.

Keywords: Combined Cycle, Gas Turbines, Mathematical Modeling, simulation, control.

1. INTRODUCTION

According to the International Energy Agency (IEA), the world electricity production is expected to grow more strongly than any other form of energy and the rate of demand in power might exceed 2.2% per year, between 2008 and 2035 [1]. Therefore, there is an increasing demand of new resources and advanced technologies to sustain the growth development and the universal coverage of electricity services. In fact, more than 65% of world's electrical energy needs are produced by fossil fuel power plants [2]. The global electricity supply industry admits that the first choice as production technology for the private investors is represented by the Combined Cycle Gas Turbine plants (CCGT). CCGT represent the connection between the energy production technologies based on fossil fuels and the evolution towards renewable and innovative sources of energy. Therefore, the energy production will rely on the use of fossil fuels, for a long time period, and the combined cycle plants will most likely meet a strong growth in the coming years.

In recent years, there is an increasing interest to the combined cycle gas turbine (CCGT), especially in countries endowed with huge natural gas resources [4]. In these countries, like our country (Algeria), the CCGTs are more attractive compared to other power system technologies with low capital costs investments, faster construction and higher operation flexibility and efficiency [5]. Moreover, combined cycle plants involved by the new combustion techniques implemented in the GT technology allow achieving lower rates of NOx emissions and a reduction in carbon dioxide emissions by up to 75% [6, 7]. This kind of power plants based on this technology, reached a high efficiency up to 60% by producing great output power compared to the conventional power plants [8, 9]. Furthermore, important increase efficiency can be reached by using natural gas instead of fossil fuels [10]. Over the time, the CCGT plants technological evolution has undergone different generations, progressing in parallel with the GT and steam cycle development. These advantages become more and more important in the current context where the operating standards and other factors concerning the environment protection are increasingly stringent. Furthermore, CCGT plants require less space than equivalent coal or nuclear stations and less constraints on site due to lower environmental impact. Besides, CCGT plants offer low operation and maintenance costs, by quality equipment designed to allow easy access for components inspection. In the coming years, along with the introduction of new standards relating to environmental protection, the installation of CCGT is expected to increase even more dramatically.

The evolution of the power system results in challenges concerning modeling and simulation. In a traditional approach, building a new engine model, is time consuming and expensive, while an effective simulation model can be developed without any prototypes being needed at the very early stages of the design. Modeling is therefore not only a mathematical workout but involves a good understanding of the system and its functionality. However, modeling is even more challenging as decisions have to be made about which phenomena and dynamics are neglected and which ones are modeled. Therefore, there is a need for simplified mathematical models of CCGTs that can be used to investigate power system stability, determine the best operating strategies, and develop contingency plans for system upsets. In this field, a great number of studies [6,7,11] has been published on gas turbines model. Several literature researches [10-13] showed that the use of simplified models can be a possible option to represent the dynamic behavior of combined cycle system for different purposes. However, the dynamic simulation is a critical procedure when the systems operate close to the limits of the process. This requires complex models that are as close as possible to real system. Therefore, numerous works already presented mathematical models for the thermal power under several disturbance conditions. Those simulations models provided a detailed study of the stability analysis of the power system. Dynamic simulation allows investigation during the transient behavior of the entire thermal power plant with its related control structures. Therefore, considerable efforts have been exerted for understanding of CCGT dynamics and to design suitable control system, and there are strong motivations for improving the power plant performance [2, 14-15]. Remarkable research activities have been carried out on modeling and simulating systems and a variety of analytical and experimental models have been developed so far to get in-depth understanding of the nonlinear behavior and dynamics of these complex systems. The information extracted from the mathematical models simulation is used extensively to investigate opportunities of future developments and innovations. Considerably, advanced control system, novel simulators and accurate simulation models that describe the full details of CCGT plants operations are valuable and necessary.

2. CCGT PLANT CONFIGURATION AND DESIGN

Combined cycle gas turbines (CCGTs), as their name signify, combine existing gas and steam technologies into one unit. They bring together the Rankine cycle from conventional steam plant and the Brayton cycle from gas turbine generators, yielding significant improvements in thermal efficiency over conventional steam plant [16]. In both types of plant, it is the inherent energy losses in the plant design that constrain their thermal efficiency. CCGT plant design has moved on from generating units based on the Brayton cycle, which typically achieved thermal efficiencies in the range 30-40 %. Now the thermal efficiency of CCGT units is extended to approximately 50-60 %.

In these power plants, the air is compressed isentropic in the compressor before being fed into a combustion chamber, where it mixes with the natural gas from the fuel supply system and burned to produce hot gases. The energy of the expanding air is then converted to mechanical power in the gas turbine, for driving the compressor that in turn converted into electrical power by a generator [17, 18]. The gases exhausted from the gas turbine are used to drive a steam turbine, by transmitting these gases through the heat recovery steam generator (HRSG). Otherwise, the use of such wasted heat in a heat-recovery steam generator (HRSG) is the basis of the 'combined-cycle gas-turbine' power plant which has been a major development of the past decades. With the heat used to generate steam in this way, the whole plant becomes a binary unit employing the features of both the Rankine and the Brayton cycles to achieve efficiencies that are simply not possible with either cycle on its own [19]. In fact, the addition of the HRSG yields to a thermal efficiency that may be 50% higher than that of the gas turbine operating in simple-cycle mode. The mechanical power produced by the steam turbine is converted into electrical power by the generator. As a result, the gas turbine provides two-thirds of the total unit power output and the steam turbine provides the other one-third.

CCGT plants present a wide range of design options and configurations relative to the number of units, the type of the steam cycle, the connection type between the thermodynamic cycles, the electrical circuits, etc. Another criterion for classification considers the possible mix of the working fluids (air/gas and water/steam), it can be with mix or without mix (e.g. Steam Injection Gas Turbine (STIG), Combined Cycle Fully Fired (CCFF)) [2]. Additional to the technical selection criteria, there is also the economic evaluation which can influence the topology of the plant, such as the investment costs, the use in base-load, part-load operations, the fuel cost and quality, the operating and maintenance cost, etc. The main technical configuration types are cited bellow:

A. Depending on the number of units

Generally, the types of plants are categorized according to the number of its component units. Typically, each GT has its own associated HRSG, and multiple HRSGs supply steam to one or more steam turbines. The steam turbine is sized to the number and capacity of supplying GTs/HRSGs [20]. For example, a combined cycle of 1-1-1 type has a GT, a HRSG and a ST, at a plant in a 2x1 configuration, two GT/HRSG trains supply to one steam turbine.

B. Depending on the steam cycle

Combined cycle power generation includes a range of steam cycle options, where each cycle can have a certain configuration satisfying a number of technical-economic considerations. The choice of the steam cycle topology depends directly on the used GT; in particular of its gas exhaust characteristics (flow, temperature). The amount of potential recoverable energy in the flue gas determines the feasibility of the different steam cycle configurations. Thus, there are installations with:

- 1 level of pressure (1P),
- 2 levels of pressure (2P),
- 2 levels of pressure with reheat (2P RH),
- 3 levels of pressure (3P),
- 3 levels of pressure with reheat (3P RH).

The large power stations are often configured 2-2-1, with a water-steam cycle with three levels of pressure and reheat (3P RH) [21].

C. Depending on the thermodynamic cycle

This configuration depends on the introduction mode of the fuel and the type of coupling between the thermodynamic cycles, there are several categories [22]:

- Cycles in series: the primary energy is introduced only in gas cycle; the steam cycle is used as a recovery unit. The thermal energy from the fuel is used in both stages of the thermodynamic cascade. This type of combined cycle provides the best thermal efficiency.
- Cycles in parallel: the primary energy is introduced simultaneously in both cycles (gas and steam). In thermodynamically terms, there is no real coupling between the two cycles, the connection is strictly technological.
- Cycles series-parallel: a combination of previous cycles, a part of the primary energy goes through the thermodynamic cascade; the other side is introduced directly in the steam cycle.

3. INFLUENCE OF AMBIENT CONDITIONS ON THE CCGT

Currently, the use of natural gas for power generation considering its cost is justified, in most cases, by high-efficiency installations, which are typical of combined cycle power plants [23]. In this type of power generation unit, the operation problems pointed out above manifest themselves, and they are aggravated as a consequence of the presence and the interconnections of the main components, namely the gas turbine, HRSG and steam turbine [24]. The operating conditions of the equipment, e.g., turbine blade cooling, exhaust temperature and exhaust steam pressure also influence CCGT performance [25, 26]. The main reason for this sensitivity is the influence of these parameters on off-design gas turbine operation, namely ambient temperature; atmospheric pressure and relative humidity are different from those under ISO conditions. Thus, the mainly approach to improve the efficiency of the combined cycle power plant is to maintain the inlet air temperature of the compressor around 15°C (ISO) and relative humidity of 100% of the gas turbine [27].

A. Ambient pressure

The influence of the atmospheric pressure is related to the air density variation, and the specific mass of the air is reduced when the ambient temperature increases, and therefore the output power reduces. At the lower ambient pressures, the air density reduces. The changed density only impacts the power output, but not the efficiency of the turbine [28]. The effect of the ambient pressure on the performance must be considered, mainly during the design phase, for once the plant is installed, the variations of this variable are neglected [28].

B. The relative humidity

Since the water changes the thermodynamic proprieties of air, this causes a variety of changes in the engine. It can be noted that the relative humidity increases with increasing temperature [28]. When the air's relative-humidity increases, the output power generated by the combined cycle plants also increases, provided the other parameters remain constant. In this case, the gas-turbine's efficiency is slightly reduced, as well as its power. However, the temperature of the gas-turbine's exhaust-gases rises, and hence the power generated by the steam cycle is increased [29].

C. Ambient temperature

Ambient temperature continues to be widely studied in relation to the operational performance of CCGT [30, 31, 32], the results showed that the increasing in the ambient temperature leads to a dropping of the output power of the gas turbine. In the other hand, the rise in ambient temperature leads to increase the fuel consumption, consequently results in flue gases losses, thermal efficiency drop, and hence more carbon dioxide emission. Other ambient factors such as atmospheric pressure, relative humidity, and wind speed also have an influence [33]. At high temperature, the air is less dense; consequently, this can decrease the gas turbine’s performance [34]. Erdem and Sevilgen [35], determine the effect of the ambient conditions on the actual gas turbine performance. The obtained results show that, when the temperature is increased higher than 15°C the loss in the power generations, it will be increased in all locations. The loss is about 2.87–0.71% of the electricity generation, compared to the annual production at standard conditions rate in hot locations. With cool the inlet temperature until 10°C the electricity production increases for about 0.27–10.28%. According to Kehlhofer et al., the gas turbine is designed to operate with a constant air volume in the compressor [36]. De Sa and Al Zubaidy, [30], has confirmed that the rise in the ambient temperature by 1 °C above ISO conditions causes the losses in the generated power output by 1.47 MW and the thermal efficiency about 0.1%. Furthermore, the effect of the cycle parameters variation on rational efficiency and exergy destruction of the plant components investigated by Sanjay [37], revealed that the more effective parameter on the performance of the CCGT is the turbine inlet temperature (TIT). Higher ambient temperatures cause a reduction in the overall thermal efficiency and power output for all configurations of the CCGT power plants. The obtained results of TIWARI,et al .[38] show that the net decrease in combined cycle efficiency is 0.04% and the variation in exergy destruction of different plant components is up to 0.35% for every 1°C rise in ambient temperature. The gas turbine performance mainly depends on the efficiency of the compressor, which is directly reliant on the airflow as well as the ambient temperature [30]. However, the ambient temperature changes, and hence the performance of the gas turbine can be affected. The obtained results study of De Sa A, Zubaidy AS [30], demonstrate that the output power and the thermal efficiency of the gas turbine depend on the ambient temperature. Therefore, it is necessary to considerate the environmental conditions to characterize correctly the thermodynamic process in GT [39].

4. COMBINED CYCLE EVOLUTION

The improvement of the material quality and the technological evolution has led to a considerable increase in efficiency and productivity of the thermal power plants. The combined cycle was considered in some depth almost as soon as the gas turbine was released from the constraints of military applications [40]. However, because of their use of gases at extremely high temperatures, early machines have suffered from limited blade life and hence they have been used only in applications where no other source of power was readily available [41]. With improvements in materials technology, this difficulty has been overcome and, nowadays, combined-cycle plants employing gas turbines form the mainstream of modern power-station development. Over the time, the CCGT plants technological evolution has undergone different generations, progressing in parallel with the GT and steam cycle development. At the beginning of 1960s, the plants efficiency was around 25 to 30% [2]. Most combined cycle power generation systems installed in the 1950s and 1960s included conventional fully-fired boilers. The efficiency of this type of combined cycle was approximately 5% to 6% higher than that of a similar conventional steam plant. Equipment to economically weld continuous spiral fins to tubes was introduced to the boiler manufacturers in 1958. Heat recovery combined cycles, which use the sensible heat in the gas turbine exhaust gas, were made feasible by enhanced gas side heat transfer by the use of resistance-welded, finned tubes. A small number of heat recovery-type combined cycles were installed in power generation applications in the 1960s. When gas turbines with capacity over 50 MW were introduced, in the 1970s, the heat recovery combined cycle experienced rapid growth in electric utility applications [2]. The 1980s and early 1990s brought a large number of natural gas-fueled systems; including plants designed for power only and those designed for power and heat (cogeneration) applications.

Nowadays, 58 – 62% LHV efficiency of advanced combined cycle power plants has been developed to light up the market requirements for fast start-up, rapid load cycling and minimum load turndown, while maintaining good part load emissions.

5. COMBINED CYCLE GAS TURBINE PERFORMANCE

Due to their attractive performance characteristics and low emission combustion system, combined cycle installations have considerable merits in power generation plants compared to the simple cycle power plants [42]. The CCGT plants have developed by combination of two different thermal power cycles, known by Brayton cycle and Ranking cycle, through the heat recovery steam generator (HRSG). This combination between the power units determine the performance of the CCGT system [43-45]. According to the study realized by Polyzakis et al [46], the more suitable cycle for the CCGT power plant is the reheated GT cycle. The study has been performed by optimization of four different gas turbine cycles to enhance the CCGT power plant performance then compared among all cases. Each proposed gas turbine cycle has been studied, and the obtained results shows that the maximum thermal efficiency of the steam turbine cycle occurs with the reheated gas turbine. The analysis study of CCGT performance of Ersayin E, Ozgener L [47] is founded on the actual data, which are collected from the control room of a CCGT power plant. This analysis, based on the first law of thermodynamics, conducted that the energy efficiency in the CCGT reach 56%. While, the main goal of the researchers gets high thermal efficiencies of the CCGT power plants up to 60% through the use of the recent developed technologies.

The push for higher outputs and efficiencies led to the development of combined cycle, requiring more gas turbines with higher firing temperatures that supported exhaust gas heat recovery to drive a steam turbine. The gas turbine cycle represents the mean source of the heat in the CCGT power plants; therefore, the more efficient CCGT power plant will result in a great saving when it is arrived at the optimal gas turbine. Attaining higher overall thermal efficiency of the CCGT requires optimizing the entire plant, specifically the three major components: the GT, the Heat Recovery Steam Generator (HRSG) and the Steam Turbine (ST) [48]. However, among the three components of the CCGT plants, the performance of the GT comes into first as the predominant influencer on the performance; with which plant efficiency can attain the 60% target and even more [49]. The selected gas turbine cycle is the most effective parts of the combined cycle through applying the optimum parameters to the performance enhancement. The complications working of GT are appeared in the thermal process, which requires fluids to work under very high temperatures and pressures [50].

A. Brayton cycle performance

Goodarzi et al. [51] examined different configurations of the Brayton cycle including the simple Brayton cycle, the regenerative Brayton cycle, and the regenerative Brayton cycle with the specified mass fraction from an energy perspective. In the proposed new configuration, the fractional of the output fluid of the first turbine goes to the regenerator and the rest goes to the second turbine. The results showed that the use of the regenerative cycle over the simple cycle leads to an increase in energy efficiency (due to the reduction in fuel required by the combustion chamber inlet) and a decrease in the output work. The increase in gas turbine inlet temperature also results in a lower rate of exergy destruction cost of the combined cycle. Ahmadi et al. [52] investigated and optimized a combined Brayton and Rankine cycle from an exergy, exergy-economic and environmental aspect. Parametric analysis is then performed to study the effect of compressor pressure ratio and gas turbine inlet temperature on the exergy efficiency and overall cost rate. The results showed that the highest amount of exergy destruction and cost rate occurred in the combustion chamber. Vandani et al. [53] examined the impact of using two different types of fuel, namely natural gas and diesel fuel, on the performance of the Brayton–Rankine hybrid system. Their results show that the efficiency can be achieved 43.11% using the fossil fuel and 42.03% for diesel fuel, under similar conditions. In addition, the annual cost of using diesel fuel is about twice the cost of operating with natural gas fuel [54].

B. Ranking cycle performance

The performances of the Rankine cycle could be improved by using organic fluids instead of steam as working agent. A possible solution is to add an organic Rankine cycle unit downstream the gas-steam combined cycle power plant, which is converted into a gas-steam-organic combined cycle power plant [55]. ORC are currently taken into account for performance enhancement by generating additional power from waste heat. The development of the ORC technology was increasingly growing after 1970. Recommendations for preliminary assessment of the potential working fluids and ORC configurations are performed in [56]. The studies show that ORC systems have lower sustainability than power plants generating power from renewable sources (hydro, wind and geothermal) but much higher than power plants operating with fossil fuels [57]. Possibility to recover waste heat from the flue gas of a 900 kW diesel engine in an ORC unit and the usage of the recovered energy in a hybrid power train is studied in [58]. Carcassci and Winchler [59] presented a thermodynamic analysis of an ORC cycle connected with an intercooled gas turbine, while Clemente et al [60] studied the possibility to recover the waste heat from the exhaust of a small scale gas turbine of 100 kW, in an ORC system. The same recovery solution is analyzed in [61] but for a medium size gas turbine. Recovery in an ORC system of the waste heat discharged into the atmosphere by the condenser of an air-conditioning unit is analyzed in [62]. The use of ORC as bottoming cycle for medium and large scale power units with gas turbine was analyzed in [63]; six organic working fluids were considered in the study. While an object-oriented approach to dynamic modeling of ORC systems is presented in [64]. The performance of a dual-loop ORC for additional power generation from the waste heat of an engine is analyzed in [65].

6. COMBINED CYCLE GAS TURBINE TRANSIENTS

During operation, these power plants are subject to a large number of transients. The transient behavior of GT reflected on the CCGT system behavior. The CCGT power plants are required to have frequent start-up/shutdowns followed by quick loading in order to regulate power generation rates according to electricity power demands that often change. The time reduction for start-up without shortening the machine lifetimes has become important for economical fuel consumption [66]. The decisive factors for rapid start-up are thermal stresses caused by temperature gradients in the thick parts of the heat recovery steam generator (HRSG) and in the steam turbine. Important functions of the CCGT power plant control system are to reduce the start-up time and to satisfy the operational constraints. In this field, some study has been dealt with the startup problem in the CCGT: A start-up schedule for a conventional (simple steam cycle) thermal power plant is usually generated by a mismatch chart using the differential temperature between the steam and steam turbine rotor metal just before the steam turbine starts [67]. The conventional control system of the CCGT power plant has basically used the same method. Nakai, et al. [68] have proposed a model predictive control for a conventional thermal power plant. This algorithm predicts the future thermal stress in the steam turbine rotor and calculates the optimal future profile of the steam flow rate. A fuzzy expert system for a CC power plant has been proposed in [69]. To obtain the startup schedule, this system uses an engineer's experiences in fuzzy rules. A nonlinear programming using a power plant dynamic model applied to a simplified single pressure CCGT power plant model has been studied. Nonetheless, the model includes many assumptions and simplifications; thus, it is not possible to study a practical problem. [70] has proposed a method to determine the practical optimal start-up schedules using a dynamic simulation and nonlinear programming. This method does not require any adjustment of the schedule parameters by engineers. In addition, a great deal with labor is not required in order to prepare the knowledge base. Some critical factors such as startup [71, 72], load change [73], shutdown [74], and variations in ambient conditions, equipment failure and other abnormal behavior exist, which can trigger transient behavior by shifting the engine's equilibrium from one steady state to another steady state [73]. This can lead to certain thermal, aerodynamic and mechanical stresses in the gas turbine, which are responsible for reduced availability, poor reliability and considerably increased maintenance cost [75]. In Ref. [76], the study is founded on the literature based statistical segregation of different phenomena causing transient behavior. It has been clarified that load change transient phenomenon has not been taken into consideration by researchers.

7. COMBINED CYCLE GAS TURBINE TECHNOLOGIES

Nowadays, combined cycle power plants operate in conjunction with wind turbine and solar energy power plants. In order to sustain this new trend, advanced combined cycle power plants have been designed with features for increased frequent operation and turndown capability [20]:

- A cooling system for the air combustion turbines, with improved dynamic control to prevent blade rubs during rapid startups,
- Exhaust stack dampers that close to retain the heat in the combustion turbine and HRSG, to get a rapid start with less thermal shock,
- High capacity super-heaters, that been able to preserve steam conditions during rapid starts and cyclic operation,
- Optimized combustion turbine control,
- Standby heating systems for the HRSG and condensate polishers to reach steam purity specifications rapidly,

- Adding a supplementary boiler to maintain condenser vacuum during shuts downs,
- Integration of the combustion turbine dry low NOx combustion system, in order to improve emissions during start up and cyclic operation,
- HRSG drums with lower thickness to accommodate rapid heating and cooling,
- High and intermediate pressure steam turbines for improved control and higher ramp rates during fast starts and cyclic operation.

8. RESEARCH ADVANCES IN THE CCGT PERFORMANCE ENHANCEMENT

Many researchers considered in the improvement of the CCGT performances. In fact, recent studies analyze key parameters and operation conditions to optimize CCGT systems [77]. Kotowicz and Brzeczek [29] proposed a methodology to improve the performance of the CCGT. It is based on the improvement of gas turbine features, and to consider another steam cycle. Jahangiri et al. [78] developed exergy, thermo-dynamical and economic analyses based on the effect of a flue gas injection system. While Kilani et al. [79] analyzed the effect of two applications of steam injection within the combustion chamber. They obtained that with an adequate steam injection process which can improve the overall cycle efficiency up to 60%. Ganjehkaviri et al. [80] developed a thermodynamic modelling of a CCGT under different designs. Ersayn et al. [81] investigated the energy and exergy performance of a CCGT as a function of its components and modifications adding new components, obtaining an improvement of first and second law efficiency, respectively, from 45% to 56% and from 24% to 50%. The use of alternative sustainable fuels is of high interest for supporting CCGT’s sustainability and viability. The use of alternative fuels affects the operation conditions of gas turbines and components [82-83].

Biogas, as an alternative fuel to natural gas, has a lower laminar flame speed, a reduced fuel range, higher requirement energy ignition, and a higher auto-ignition temperature. These features cause its use in natural gas conventional combustion chambers to not give a complete combustion processes. Chacartegui et al. [84, 85] investigated the effects of the use of syngas fuel on the performance and the environmental impact of CCGT. They focused on the difference of fuel characteristics and combustion products of main components, analyzing the Low Heating Values (LHV) for various syngas combinations. They also analyzed the effect of syngas combustion, emissions and combustion chamber performance. In fact, various elements like gas turbines are influenced by the adoption of syngas fuels using fossil or vegetal sources [86,87]. As described in [86], the use of syngas fuel and the derived combustion products affects the performance and the design of a CCGT power plant. Due to the limited operational problems of the gas turbine elements, Kim et al. [88] deepened the study of energy performance limits in a combined cycle power plant. Recent studies are based on the natural gas/syngas use mixtures in order to obtain the optimal performance in terms of fuel efficiency and also flame velocity and propagation with a lower environmental impact in terms of pollutant emissions [89]. The study in [90] develops energy, environmental and economic analyses of a modern combined cycle power plant with the objective to evaluate the potential benefits for a combined cycle power plant running with alternative fuels in an area with high biomass availability, in order to reduce costs and global emissions. Different components and key parameters are examined. In this context, numerical simulation represents today an important tool for the prevision effects in use of syngas [91, 92].

In addition to the above-mentioned purposes, effects of fuel control on transient behavior and combustion chamber’s transients have also been studied. For instance, the authors Ma et al. [93] have developed a transient model for the fuel control strategy developed for the starter of gas turbine. Likewise, Wang et al. [94] have studied the effect of incorporation of fuel control system along with the generic control system on the time delay during transient behavior. Moreover, Singh et al. [95] have investigated the effect of variation in the fuel’s lower heating value on the transient behavior. Rosfjord and Cohen [96] have suggested and utilized a new test facility to evaluate the transient behaviors occurring in the combustor. The study has been proved helpful for air estimation and fuel flow time variation rates along with air temperature.

Shi et al. [97] have done transient performance simulation to observe the effect of compressibility on the transient behavior, while Novikov [98] has studied the effects of inlet pressure distortion and component deterioration on the transient operation.

Recently, an interesting solution called Integrated Gasification Combined Cycle (IGCC) developed envisages the coal exploitation, after the gasification process. IGCC technology converts the coal into a cleaner burning synthesis gas (syngas) and as its name suggests, combines the coal gasification with combined-cycle technology. Actually IGCC represents the most efficient and clean way to use the coal for the electricity production [99-100].

9. MODELING AND CONTROL SYSTEM DEVELOPMENT

Recent CCGT plants have to be designed for maximum efficiency, lower emissions and high flexibility with regard to load changes, and transient behaviors. Investigation into the dynamic performance of these plants requires detailed information of the process. Dynamic simulation is also a cost-efficient tool to sustain unit commissioning and regular operation by estimating component life time and directing maintenance [101]. Modern simulation strategies combine a graphical user interface with detailed models for flow, thermodynamics and heat transfer. The inherent complexity of the governing differential conservation equations and the numerical solution methods make the dynamic simulation codes very sophisticated computer software with long development periods [102].

Since control strategy is the most crucial entity during transient operation for insurance of stable engine operation. Many studies have been carried out in order to develop control system strategies. However, well-known controllers such as PI and PID have been developed for these power plants. Proportional-integral-derivative (PID) control scheme has been implemented to capture the entire transient operation in mechanical drive GT power station [103]. However, it emerged as a holistic model and benefitted in monitoring the surging, startup and slow transient operation occurring inside the centrifugal compressor section [101]. Previous control system simulators have based on simple block diagram and generalized type programs [104]. Although, these simulators are very simple and easy to develop but limited in dynamic studies, by considering few dynamic variables. Moreover, generalized type simulators proved to be time consuming in solving the Jacobian matrix. It is very important to improve the use of more advanced control strategies like fuzzy, neural or predictive optimal control [101]. A new control system is proposed in [105] for the robust decentralized stabilization of multi-machine power systems based on linear matrix inequalities(LMI). Experimental results indicate that transient stability can be significantly improved with this approach. Artificial neural network based system identification for a Single-Shaft Gas Turbine has been proposed in the research paper of Asgari et al [106]. While, Samet et.al, [107] and Kheradmand et al. [108] have proposed the hybrid artificial neural network (ANN) approach with three-layer for estimating the heat rate and performance of a power plant. Takagi and Sugeno [109] have proposed adaptive network as a function of the system equivalent to a first-order fuzzy inference system. Ganjehkaviri et al. [110] have proposed the multi-objective optimization for the comprehensive thermodynamic model of a combined cycle power plant with different values of the steam quality at steam turbine outlet. Mohammed, M. K et al in [111], presented a study for modelling codes for assessing the performance of the CCGT plants, and optimizing several parameters for best performance and Adaptive Neuro-Fuzzy System (ANFIS), which has been introduced to measure the optimum parameters.

Recently, a dynamic model for hybrid gas turbine and wind turbine system has been developed by Tsoutsanis and Meskin [112] in order to design a controller and optimize its operation in hybrid mode. Park [113] has also developed a hybrid dynamic model of a distributed energy system. Similarly, Kong and Kim [114] have focused on performance optimization and controller design of a turbojet engine. Meanwhile, a transient modeling study for control system diagnosis of a single shaft industrial gas turbine has been stated by Bettochi et al. [115].

10. MATHEMATICAL MODELING AND SIMULATION

The modeling dynamic systems have always been a challenging research topic due to the fact that mathematical models cannot accurately describe nature. Although there are no guidelines regarding the model construction methodology. Today, a large number of different kind of models are used. These models have always been an important method to investigate the performance and behavior of the systems. They account for the size as well as the characteristic features of the underlying power system as reported in [116].

A. *Mathematical modeling*

Mathematical modeling has always been an important procedure as well as economical tool of investigation and examination of the dynamic systems. Mathematical models contribute to a better understanding of the processes and play an important role for increasing the efficiency and flexibility of thermal power plants. However, modeling means abstraction. So, the result of the modeling process is a model that is an abstract representation of the real system. If we have done everything correctly, it is valid within a defined context which is derived from the question we would like to answer. In the reference study [117], is stated that we have to trust that the modeler has chosen a proper level of abstraction and assume that his knowledge of the real system is sufficient to describe its behavior. Pfenninger et al. [118] think that modelers must also make sure to avoid the trap of modeling what is easily quantifiable rather than what are the essential driving variables of the system. The modeler has to decide for himself which aspect have to be modeled in detail and which ones can be abstracted to what extent, since there is no solid foundation, no established methodology that can be used to derive the experimental frame needed to answer specific questions [117]. In fact, the question about the correctness of models “Are all Models Wrong?” is answered by George E. P. Box in the mid 1970 with his famous quote: All models are wrong, some are useful. The challenges that arise from this for the creation of models are summarized by him as follows: Since all models are wrong the scientist must be alert to what is importantly wrong [117]. Rowen in his paper affirm that there are no guidelines that can be put down with regard to how far model simplification should be carried since it is very much a function of the size and characteristics of the connected system. Considerable engineering judgment and detailed knowledge of equipment characteristics are required to insure against over simplification. According to Saravanamutto et al [119], the mathematical model is required to be flexible enough, readily understandable, and must give reliable results. So, all the mathematical models have distinct domain and limitations of validity (Ljung and Glad,1994). However, since mathematical models are developed by utilizing dynamic mathematical and thermodynamic equation that defines the nonlinearity of the system, these models have always been an important method to investigate the performance and behavior of the systems. The mathematical description and model development of major thermal components, such as the plate-frame heat exchanger, plate-fin heat sink, and fluid mixer, etc, are described, in detail, in [19, 120,121]. Other hydraulic components used in the thermal system including valves, water reservoirs, pumps, and pipes were modeled and validated on component level [122].

B. Models classification

Several kinds of models may be approached from different points of view, and they have been built from different perspectives and for different purposes. The types of models range from those that examine specific aspects of the system in detail to those that attempt to model the system as a whole.

Adrian. T [2] expected that, a wide range of the proposed models for the CCGT are mainly based on three aspects: models based on manufacturer tables/functions, models based on identification and models based on physical equation, which are most common used. The models based on physical equation are represented in several ways and with different degrees of complexity.

According to ASGARI. H [106], the models of industrial systems had been classified into two main categories including black-box and white-box models. A white-box model is used when there is enough knowledge about the physics of the system. White box models are also termed as physical models or first principle models because they are based on a profound information about the physics of gas turbine. While, a black-box model is used when no or slight information is available about the physics of the system [106,123]. In addition to white-box and black-box methods, the expression gray-box may be also used when an empirical model is improved by utilizing a certain available level of understanding about the system [124]. In this case, experiments can be combined with mathematical model building to improve model accuracy [123]. However, a frequently employed modeling technique is the gray-box identification supported by nonlinear approaches. Some works employed behavioral modeling in distinction (Pires et al., 2018; Meyer et al., 2015; Mohammadi and Montazeri-Gh, 2015; Asgari et al., 2014). Also, some researchers employed their own nonlinear model simulation frameworks, or developed simplified physics based models (Gulen and Kim, 2014).

Another classification of simulation models is cited in [122], where it is discerned that the simulation models can be broadly classified as analog models, hybrid models, and digital simulation models. Analog models played key role in early 19th century with the notable work by Larrowe, Spencer and Saravanamutto et al. [119,125]. They developed a full operating range of gas turbine analog model. The analog models supported the development of control strategies for gas turbine engine in the early stages. Later the hybrid models further advanced these analog gas turbine models with better accuracy. The dawn of digital computer simulation models has overtaken the ability of analog and hybrid models with its speed and capability of complex calculation. Currently digital computer simulation models are widely used to effectively capture the gas turbines nonlinearities and secondary effects.

In the literature a large number of different kinds of simplified models are used to examine specific processes of the system for different aspects of study. Simplified models are still able to capture dynamics relating to the power system, even though they are not as detailed and complicated as the physical models. Their different degree of complexity makes them suitable for different types of studies. Rowen's Model involves a simplified mathematical model for heavy duty gas turbines. It has been utilized to investigate the impacts of governor on system operation [126]. The model validated against the actual operation data and found to be adequate for a real life implementation [127]. The IEEE model has also been further developed in [128] to take into account effects such as the use of a part of the overall air flow in order to cool the turbine blades. The enhanced model was found to be able to simulate the dynamic behavior of the gas turbine with the required accuracy. The GAST model was one of the most commonly used dynamic models for the governor control [126]. This was partly due to the simplicity of the model and partly due to the fact that it was once WECC (Western Electricity Coordinating Council) compliant. The GAST Model has been superseded by other more accurate models such as the GGOV1 model. Since early 2001, WECC has proposed new criteria for Frequency Responsive Reserves (FRR) making the need to develop a more accurate governor model for dynamic simulations imperative [129, 130]. A model was developed using measured responses and data collected from two trip tests performed on the 18th May 2001. It should be noted that the GGOV1 model is a general model for all thermal units and the developed model can be utilized for representing gas turbines with suitable parameters in the various control blocks. Recognizing the increasing importance of the gas turbines, a CIGRE Task Force for gas and steam turbines in combine-cycle power plants, has developed a model of combined cycle power plant [131]. To be able to analyze incidents with abnormal system frequency behavior, the frequency dependence (FD model) of the gas turbine model must be taken into account. This was the main aim of K. Kunitomi et al [132], the proposed model based on the physical principles is developed in order to clarify the effects that shaft speed and ambient temperature has on shaft speed. As there are many aero derivative gas turbines connected to the network (especially for smaller machine ratings), a model for an aero derivative gas turbine was also developed [133]. In terms of the format of the block diagram it is similar to that of the Rowen's model. However, instead of a single speed signal going into the low value selector, there are now two speed signals. While the detailed model [134] consists of the power generation units and the control system, and it is valid for a single-shaft combined cycle plant, and mainly it is based on the IEEE model proposed in [135, 136]. Vournas [134] extends the results of Kakimoto and Baba [137] by including a supervisory control of the combustion temperature. This model extends the gas turbine modeling by adding a simplified steam turbine model.

C. Simulation tools

For verification of the overall plant design and control concept, a sophisticated simulation model is required that can be considered a virtual representation of all the essential systems for plant dynamics. The structure models solve the problem by deviating from normal conditions that are often associated with approximations of experimental relationships, linearization and real processes [138]. The complexity of these simulation models, based on differential equation systems and numerical solution procedures, involves a computational effort that is unsuitable for optimization purposes [139].

As it is predicted, so far, a frequently employed modeling technique is the gray-box identification supported by nonlinear approaches such as Wiener modeling, NARX structures, artificial neural network-based modeling, and multivariable model predictive control or hybrid fuzzy models [140]. These models are developed by utilizing dynamic mathematical and thermodynamic equation that defines the nonlinearity of the system. These nonlinear equations are simplified by assuming some values as ideal and then applying some linearization techniques using MATLAB simulation environment [141]. Matlab/Simulink offer the researcher an open interface for modeling of non-standard components.

Previous works already presented models for the thermal power block of the studied CCGT. Some of them show simulation results combined with the results produced by the computer analysis tool called ANATEM. Those simulations supported the stability analysis of the power system near the studied CCGT under several disturbance conditions (Rendon et al., 2015, 2014). A detailed of the stability analysis of the power system in a possible islanding, using electromechanical simulation in ANATEM with the support of a software tool developed by the research team, can be reviewed at [142]. The PROOSIS simulator has been introduced in simulating of gas turbine transients [143]. PROOSIS is a new software for simulation in the area of propulsion allows more precise pneumatic volume description that includes the momentum conservation law.

Several advanced codes and commercial software programs for steady state and dynamic process simulation of thermal power plants are available, E.G. EBSILON professional, APROS and ASPEN Plus dynamics. Some programs provide specialized component libraries for steady state and time dependent simulation of energy systems, including combined cycle, simple cycle plants and many others. For instance, Gate Cycle, Aspen or Thermoflex, Aspen HYSIS software used for the simulation of the CCGT power plants [144]. Furthermore, complex physical systems with mechanical and control subcomponents can be modeled using the non-proprietary Object Oriented, Equation based language (MODELICA) [139]. The mathematical back ground of these programs is based on the balance equations of mass, momentum, species and energy. The complexity of these equations and the required numerical solution algorithms depends on, firstly on the problem's state: steady state, quasi-steady or dynamic, and secondly on the dimension of flow problem (zero-dimensional, one-dimensional, two-dimensional or three-dimensional) [145]. Different simulation environments such as DYMOLA, JMODELICA. ORG and SIMULATIONX, are available.

D. Simulation methods

The diversity of modeling CCGT plants can be appreciated through investigation of the research objective and the latest operational requirements for achieving higher GT efficiency and optimal dynamic behavior. Therefore, different simulation methods are performed in order to investigate the dynamic performance of thermal power plants.

Gas path analysis

This method was efficiently used in industries previously. Gas path analysis come in the forms of inverse, linear and nonlinear methods [146], and can be used as performance prediction method or as a performance diagnostic method with reliable result accuracy. The main advantage of this method is less computation time. The main drawback of this method is still the characteristic maps of compressor and turbine, which is required to run the simulation calculations. For more details about this method, the reader can be referred to research papers of Mathioudakis et al. [147] and Simon et al. [148].

Component matching

This method is one of the reliable and accurate methods for gas turbine simulation, it had been widely accepted in industry. The principle of the component matching method is flow compatibility and work compatibility, i.e. the conservation of mass in the system and work matches between turbine, compressor and load. The solution converges when those criteria are satisfied. The main advantage of this method is the ease of implementation and can be flexible for end user [149].

According to Saravanamutto [119] and Kurzke [150], component map matching method is better suited for non-linear off-design simulation of gas turbines mainly because of its flexible approach, reliability, less complex and better accuracy. Both have done extensive work from a rigorous hand written calculations to complex highly accurate digital computer simulations of gas turbine. Both solve mathematical non-linear set of gas turbine system equations iteratively, based on their work summary of component matching modeling method. Prominent studies relating to this method was done by Saravanamutto [119], Muir [151], Walsh and Fletcher [152].

Stage stacking method

In this method a compressor characteristic data is anticipated using stage wise data available after processing from the running conditions [153]. This characteristic data can be exploitable in the designing of new gas turbine engines.

Artificial Neural Network (ANN)

ANN method is an advanced gas turbine simulation method that is currently in a way of development. The artificial neural network concept is based on biological neuron interactions inside the brain. The ANN design can range from a single layer perception neural network to complicated perception neural network. The advantage of ANN is only when all the possible data cases are available otherwise it loses its convergence when a new boundary condition is applied [154]. More information about this method can be found in the studies of Andre Lazzaretto and Andrea Toffolo [155], Sampath et al. [156].

Kalman filter method

The Kalman filter is a type off-design simulation method for gas turbine performance simulation, it is an iterative method, with a number of measurements in function of time, and these set of measurement is known as Kalman filter gains. These measurements will have error associated and it is reduced after several predictions with continuous iteration. However, this method still less accurate than component matching method [157].

Fuzzy logic method

The fuzzy logic method is a simulation method largely used for gas turbine engine wellbeing monitoring purpose. This method supports the study on engine characteristics when there are high uncertainties in the measured data and is found to be very effective way of prediction when there are more data. Details regarding this method can be referred to the research studies of Gunettiet al. [158], Kyriazis et al. [159].

Computational Fluid Dynamics (CFD)

This method is an in depth finite element or finite difference modeling methods, mainly used to understand fluid flow characteristics of a particular component. In gas turbine applications it's specifically concentrated on analyzing gas turbine components including compressor, combustor, and turbine, …etc, independently in order to understand their flow and heat transfer. CFD has capabilities to accurately predict the engine behavior that is working in a dynamic environment. Though CFD is able to produce accurate results, it is not often used for off-design simulation of gas turbines as it is not suitable at system-level. for further understanding on this method, the reader can check the research paper of Tomita et al. [160].

Wittenberg's method

This method can predict the gas turbine off-design characteristics without using component maps. The construction of this model requires thermodynamic relationship and good assumptions of boundary conditions to solve the governing equations. This method founded in 1976, and it can be considered as an advanced gas turbine simulation method. More information about this method can be referred from Philip P. Walsh and Paul Fletcher [161].

11. CONTROL SYSTEMS IN A CCGT

The increasing complexity of electric power systems depends on the demands and operational requirements, which leads to the need for continuing improvements in power plant performance and control. In the CCGT power plant, the control system is required to guarantee the correct operation of the whole process. The power load must be adjusted to the instantaneous requests of the power grid, with the highest possible thermodynamic efficiency. Plant durability and safety must also be assured (Moelbak and Mortensen, 2003) [162]. For this raison, the power system controls attempt to restitute the system from an off-normal operating state to a normal state.

A. Control objectives

The objective of control is to impact on the behavior of dynamic systems. Achieving fast and accurate control, with aim of assuring stability and robustness in the presence of perturbations. This consists of maintaining the outputs of the system at its assigned values, or forcing them to follow suggested time functions [163]. However, the control problem is to use all available data at every instant and determine the control inputs to the system.

System theoretical properties such as controllability, observability, stability, and detectability were investigated in the 1960s and 1970s, and the results have been used to stabilize and control such systems using state feedback. Later on, the methods have been extended to control both single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems, in which all the state variables are not accessible, through the use of observers [163]. Many of the concepts and methods developed for the control of a single dynamic system have been also extended to larger classes of systems where two or more subsystems are interconnected to achieve different objectives. Classical adaptive control deals with the control of linear, time-invariant dynamic systems, when some of the parameters are unknown [163]. However, current research in control theory includes many problems related to the decentralized control of linear systems using incomplete information about their interconnections.

During the period 1970 to 1980, the emphasis has been on generating adaptive laws that would assure the stability of the overall system, and the asymptotic convergence of the performance of the adaptive system to that predicted by linear theory. Generally, multi-SISO control systems based on frequency decoupling are characterized by satisfactory performance when load variations are smooth and small [163]. This condition is satisfied in normal operation, where the load demand profile does not change suddenly, and when startup and shutdown are safety-compliant procedures. Plant interactions are no longer compensated by the control system when sudden and significant changes of the power demand are observed. Significant oscillation of the thermal variables occurs with an impact on the thermal stress of metal parts, in order to avoid the overshoot of temperatures and pressures, and to improve the load-following characteristics of the control system.

B. Control strategies

Research studies have suggested a number of strategies, such as adaptive control that attempt to improve overall control of turbo-generator systems, extending their operational stability limits (Wu and Hogg, 1991) [164]. The main difficulty with adaptive control strategies lies in the robustness of the parameter estimation stage. So, if a self-tuning controller is to be a practical prospect, it must incorporate a reliable jacketing scheme. One solution to these problems is to obtain an accurate non-linear model of the plant, and use this in an appropriate control scheme. However, these methods tend to be very complex, which have had limited attainment in industry [165]. Recently, neural networks have generated considerable interest as an alternative nonlinear modeling tool (Hunt et al., 1992), Manipulating the ability of the neural network to approximate arbitrarily non-linear vector functions and combining this with dynamic elements such as integrators, filters or delays, yields a powerful, so far relatively easily applied modeling technique [162].

The efforts of the industrial community have been directed in part to the development of intelligent load-tracking systems that limit the effect of coupling. Klefenz and Krieger (1992) [166] suggested a control system that introduces a delay change to the load set-point, allowing optimised use of the energy stored in the boiler. Clearly, coupling sets a trade-off between load-tracking needs and the reduction of thermal stresses. With the same intent, Lausterer and Kallina (1994) [167] introduced a model-based estimator of the load margin, which modifies the control system set-points in order to achieve smoother evolution of the thermal variables. Tong and Yu [168] presented a dynamic model of a micro turbine and its nonlinear PID controller. Junghui and Tien-Chih [169] presented a new control approach by employing a PID controller and a linearized neural network model. Their research objective was to make a balance between nonlinear and conventional linear control designs in order to improve the control performance for the nonlinear systems.

Many alternative control configurations and methods, based on modern techniques, have also been suggested by researchers in academic institutions. The control structure adopted in these works is of extreme interest. For instance, Cipriano [170] discussed implementation of fuzzy predictive control for power plants using nonlinear models based on fuzzy expert systems, and using fuzzy logic to characterize the objective function and the constraints. Other studies have been devoted to the adoption of solutions based on fuzzy logic (Ben Abdennour and Lee, 1996) [171], hybrid supervision systems (Garcia et al., 1995) [172], and genetic algorithms (Dimeo and Lee, 1994) [173].

Bemporad et al. (1997) [174] and Angeli and Mosca (1999) propose a reference governor at the supervisory level. Adopting a state space representation, the objective function was formed by the minimization of the reference trajectory error. The algorithms were developed using a state space representation. A different approach for a reference governor with the same objective was proposed by Gilbert and Kolmanovsky (1999) [175]. In this case, the reference governor was defined by a non-linear pre-filter. Optimal and robust control techniques (LQG,$\mathcal{H}\infty$), have been adopted by Hangstrup (1998) [176] and Mortensen et al. (1998). Similarly, the □ ∞ techniques are used by Zhao et al. (1999) [177] in a coal-fired power plant.

In power systems, neural networks have been applied to load forecasting, alarm processing and system diagnostics. Sisworahardjo et al. [178] presented a neural network controller for power plant MGTs. They applied both PI and ANN controllers to control voltage, speed, temperature and output power. They concluded that ANN-based controller had a better performance in terms of error measures. Sahin et al. [179] develop ANN-based MPC for control of processes. They proposed a neural network approach for a nonlinear model predictive control (NMPC), and showed that the MPC can be effectively employed to control nonlinear industrial processes without linearization requirement. Bartolini et al. [180] presented application of ANN and adaptive network based fuzzy inference system (ANFIS) to MGTs. Nikpey et al. [181] developed an ANN-based model for monitoring of combined heat and power

MGTs by using the data collected from a modified MGT on a test rig.

The design of innovative control solutions has recently been promoted by several industries that build thermal power plants. ABB Simcon is among the companies that expressly cite the advantages of MIMO controls applied to thermal plant [162]. Modem configurations like those developed by Toshiba or Siemens have improved supervisory systems based on the most recent advances in the field of distributed control systems and communication procedures.

12. CONCLUSION

In this paper a brief review has been stated about combined cycle gas turbine CCGT plant. The survey expounded from different point of view namely: the CCGT design, the mathematical modeling and simulation. Furthermore, the control objectives and strategies have been discussed.

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