Modeling of Combined-Cycle Power Plants for Power System Studies

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A paper presented on behalf of CIGRE TF on "Modeling of gas turbine and steam turbines in Combined-Cycle Power Plants"

***Abstract*—This paper presents a brief summary of the Technical Brochure developed by the CIGRE task force 25, under the Advisory Group 02 of the Study Committee 38, on the modeling of gas turbines and steam turbines in combined-cycle power plants. The Technical Brochure, to be published by CIGRE Central Office, was the result of over eighteen months of collaborative work amongst 27 members and contributors from 11 countries.**

***Index Terms*—CIGRE Task Force, Combined-Cycle, Turbine-Governor Modeling.**

I. INTRODUCTION

Due to their advantages in overall plant efficiency and lower emissions as compared to conventional coal fired power plants, combined-cycle power plants have gained popularity and are beginning to account for a significant portion of the generation mix in many power systems around the world. Approximately two-thirds of the generation capacity in a combined-cycle power plant is produced by gas turbines. Gas turbines and their controls are significantly different from fossil-fuel steam-turbine power plants. In particular, the maximum power output of a gas turbine is highly dependent on the environmental ambient conditions because the gas turbine thermal cycle is an open cycle using atmospheric air as its working fluid. The maximum power output of the turbine is also dependent on the deviation of its operating frequency from its rated speed.

In an effort to provide the industry with a single document that would summarize the unique characteristics, controls and protection of combined-cycle power plants and recommendations on how to model them in power system studies, the CIGRE TF 25, under the Advisory Group 02 of Study Committee 38 was developed in July 2001[1]. The charter for this Task Force was to develop a technical brochure, to be published by CIGRE, to cover this important subject. The document has now been completed and is soon to be reviewed and subsequently published by CIGRE. This paper summarizes some of the key contents of the report and invites all anxious readers to consult the final CIGRE report, which is soon to be published.

This document is the result of a collaborative effort by manufacturers, utility engineers, consultants and research organizations around the world on the subject of modeling combined-cycle power plants for the purpose of power system studies. Power system studies can be, but are not limited to, analysis of the following nature:

1. Study of the impact of proposed new generating facilities on an existing power system,
2. Study of system small-signal and/or transient stability,
3. Study of large system frequency disturbances, and
4. Study of reactive/voltage stability of a power system.

In all of the studies mentioned above there is a need for an appropriate level of modeling detail. Some require a greater focus on the electrical components of the system and power plants while others require as much attention be given to appropriate modeling of the mechanical systems of power plants. In combined-cycle power plants the electrical components such as the generator and its excitation system are similar in nature to a conventional fossil-fuel power plant and detailed description of these elements and appropriate models can be found in other documents [1, 2 & 3]. The CIGRE document focuses on the controls and protections associated with gas turbines and steam turbines in combined-cycle power plants and the modeling of these elements of the plant in power system studies.

The layout of the document is as follows:

Chapter 1 provides a brief introduction to the subject.

Chapter 2 is an overview of the various types and configurations of combined-cycle power plants, together with a qualitative review of control and protection strategies unique to gas turbines and steam turbines in combined cycle power plants.

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[1] The Study Committee structure of CIGRE changed in 2002, however since the work of this task force was nearing its end its name as initially incepted has been retained.

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Chapter 3 gives the perspective of numerous utilities from around the world on their experiences with combined-cycle power plants, and their concerns with the models currently available in commercially available software. They also describe the phenomena often requiring simulation.

Chapter 4 provides a discussion of modeling combined-cycle power plants and documents generic models that can be used to model gas turbines and steam turbines in combined-cycle power plants for most of the major manufacturers. Recommendations are given on sound modeling practice as well as some typical data for combined-cycle power plant models.

Chapter 5 provides a detailed account of model assessment with qualitative descriptions of sound practices for field-testing of units and expected unit performance.

Chapter 6 summarizes the contents of the document together with recommendations for model usage.

The rest of this paper gives a very brief description of the contents of each of the chapters of the report.

II. COMBINED-CYCLE POWER PLANT OVERVIEW

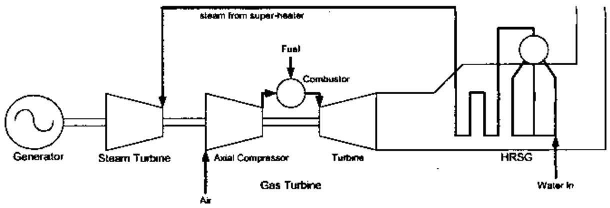
A combined cycle power plant, in its simplest form, consists of a gas turbine, a steam turbine, a heat-recovery steam generator (HRSG), and an electric generator. A primary advantage of combined cycle plants is improved overall plant efficiency. The total thermal efficiency of a such plants is significantly higher than that of a conventional fossil fuel plant. The higher thermal efficiency is due to the greater utilization of the total enthalpy produced by the combustion process in the gas turbine. A typical simple-cycle conventional fossil fuel plant has an efficiency of 30-35%, while a combined-cycle power plant can have efficiencies exceeding 55%.

The combined-cycle plant represents the integration of two cycles, one being the "topping" or high temperature cycle (the gas turbine Brayton cycle) and the other being the "bottoming" or low temperature cycle (the steam turbine Rankine cycle). The two cycles are coupled by means of a heat exchanger from the gas turbine exhaust gas in the heat recovery steam generator (HRSG) to produce steam.

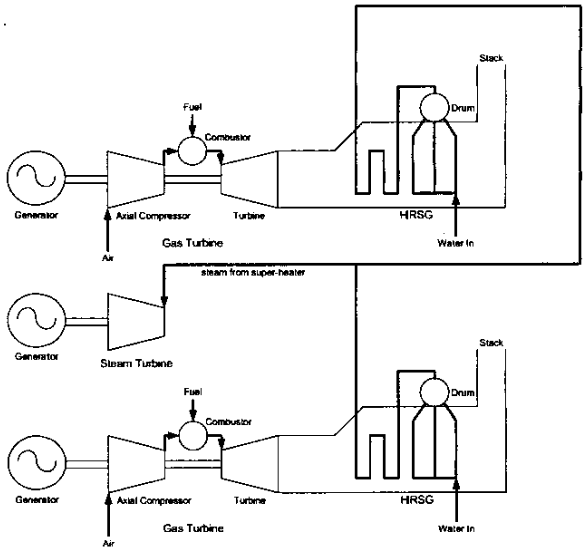
Combined-cycle units can be configured in a number of arrangements. These can be categorized into two main groups:

- Single-shaft units where the gas turbine, steam turbine and electrical generator are all in tandem on a single rotating mechanical shaft, and
- Multi-shaft units where one or more gas turbine each typically with its own HRSG, feeding steam to a single steam turbine, all on separate shafts with separate generators.

Examples of these configurations are shown in Figure 1.



(a) Single-shaft combined-cycle power plant



(b) multi-shaft combined-cycle power plant

Figure 1: Combined-cycle power plant configurations

Cogeneration is the sequential production of the heat necessary for an industrial process (generally in the form of steam) and power production by means of recovery of energy from this production. The steam requirements of the process (steam volume, pressure, and temperature) determine the optimal system configuration. If steam requirements are different than those resulting from a standard cycle, for example if significantly more steam is required, supplemental firing of the HRSG can be incorporated. Thus, supplementary firing is most often applied in combined-cycle cogeneration plants where the amounts of process steam must be varied independently of the electric power generated. Supplementary-fired units will typically have an overall lower thermal efficiency than the standard combined-cycle power plants.

The gas turbine consists of an axial compressor, combustion chambers and a turbine. These three elements form the thermal block complemented by the air intake system, the exhaust system, auxiliaries and controls. At the compressor inlet casing, air is drawn into the axial compressor and compressed through multiple stages of stator and rotor blades. At each stage, the rotor blades add kinetic energy to the air while the stator blades convert the kinetic energy to potential energy by raising the static pressure of the air. The net pressure ratio of the entire axial compressor is typically between 15 to 20. The compressed air exiting the axial compressor is then mixed with fuel in the combustion chamber, where the combustion process takes place. The hot gas resulting from the combustion process is expanded through a multi-stage turbine to drive the generator and the compressor.

The exhaust gas flow and the temperature of the exhaust gas determine the power input to the heat recovery steam generator. The fuel flow determines the power output of a gas turbine. The fuel flow and airflow together determine the firing temperature, which is the gas temperature at the exit of the combustion chamber. The fuel flow and airflow are adjusted based on the measurement of the exhaust temperature and the compressor pressure ratio in order to keep the firing temperature below a design limit. The compressor pressure ratio is determined from measurements of the inlet and discharge air pressures of the compressor.

The airflow can be adjusted by changing the angular position of the variable inlet guide vanes (VIGVs). Inlet guide vanes are essentially the first few stages of stator blades within the axial-compressor assembly. By reducing the airflow, the exhaust temperature is kept high at reduced loading levels to maintain the desired level of the heat transfer into the HRSG and maintain an overall higher plant efficiency. When the gas turbine is loaded close to base load, the VIGVs are wide open. The airflow is a function of the VIGV angle, ambient temperature at compressor inlet, atmospheric pressure, and the shaft speed.

There are different types of combustion chamber design, which are discussed in the CIGRE document. Also, it should be noted that gas turbines used for power generation can be classified into two categories (i) heavy-duty gas turbines, and (ii) aero-derivative gas turbines.

The key difference between heavy-duty gas turbines and aero-derivatives is that as seen from the electrical network the combined moment of inertia of the turbine and generator (H) is significantly higher for a heavy-duty gas turbine as compared to a typical aero-derivative turbine. This is because typically for an aero-derivative unit the power turbine and generator are on a separate mechanical shaft than the high-pressure turbine and axial compressor.

The heat recovery steam generator (HRSG) is the link between the gas turbine and the steam turbine process. The HRSG can be either a purely unfired boiler creating steam strictly from the heat extracted from the gas turbine exhaust, or can have added supplemental firing capability. The function of the HRSG is to convert the exhaust energy of the gas turbine into steam.

The steam turbine in a combined cycle power plant is similar to that in conventional plants. The major difference is in the control philosophy of the turbine.

In a combined cycle system, the steam turbine can be operated in two different modes, sliding pressure or fixed steam inlet pressure control. In practice, a combination of these operation modes is common for combined-cycle power plants, depending on the level of power output.

During sliding pressure control, the throttling or control valves are fully open. The steam pressure is a function of the steam mass flow entering the steam turbine. The load (power output) of the steam turbine depends on the mass flow and is not directly controlled. Thus the load on the steam turbine can only be increased by increasing the steam flow, which, of course, involves generating more steam in the HRSG and generally requires an increase in heat from the gas turbines or supplemental firing, if present. Thus steam units operating in sliding pressure mode will not respond significantly to governor action in the first seconds following an event on the power system, and may take a minute to several minutes to respond with a significant increase in power. When operating near full power, most combined cycle plants operate with sliding pressure control of the steam turbine

Plant Controls

The electrical output of a combined-cycle power plant without supplementary firing is controlled by the gas turbine only. The steam turbine will follow the gas turbine by generating power with whatever steam is available from the HRSG. After a gas turbine load change, the steam turbine load will adjust automatically with a few minutes delay dependent on the response of the HRSG. There have been suggestions that independent load/frequency control of the steam turbine should be provided for sudden load changes. However, such systems would require the steam turbine to be operated under continuous throttle control, resulting in significantly lower efficiencies at full and part load conditions.

In order to sustain stable operation and extend the life of the gas turbines, a frequency dead-band may be introduced in the control system within which the plant will not respond (for example, in the US, typically a deadband of 0.025% is introduced into the speed governor control loop). Outside this dead-band, a droop setting is followed. The droop characteristic setting is defined during planning phase by the grid operator and is in the range of 3 to 8 %, (typically 4 to 5 %). Combined cycle plants can be operated to supply frequency support (spinning reserve). For frequency support, the gas turbines are typically operated between 40 and 95% load, resulting in a proportionate partial loading of the steam turbine.

Additional details on the specifics of the gas turbine and steam turbine controls can be found in the CIGRE TF document.

III. UTILITY PERSPECTIVE

Chapter 3 of the document gives a detailed account of the experience of various utilities around the world with combined-cycle generation.

As is evident from the discussion, electric power systems vary from large and robust to very small, and from tightly interconnected to weakly linked. One thing that is clear is that simple-cycle gas turbines and combined-cycle power plants will be a significant part of total installed capacity for many systems. These units are operated in base load, load following and peaking duty. It is also clear that utilities are concerned about the security of the electric power system and the effect simple-cycle gas turbines and combined-cycle power plants will have on security. Thus, the modeling of these plants is becoming of greater importance. A major challenge facing utilities is to understand and accurately predict actual system behavior in light of new equipment (combined-cycle power plants) and in some cases new operating realities due to competition.

IV. MODELING OF COMBINED CYCLE POWER PLANTS FOR POWER SYSTEM SIMULATIONS

A thorough discussion on model is provided in the CIGRE document together with typical parameters for proposed generic models capable of emulating the expected response characteristics of a combined-cycle power plant for the purpose of power system studies. Figure 2 and 3 show the proposed models.

The models presented here are intended for modeling any combined-cycle power plant in a grid study. Where studies are more focused on the performance of a particular plant or are focused on simulating specific test results pertaining to a specific unit, a more detailed model may need to be used and the advice of the manufacturer or other experts should be sought.

The following points are pertinent with respect to modeling combined-cycle power plants for power system studies:

1. To represent the major control loops associated with the dynamic response of a gas turbine during system disturbances, including the dependence of the gas turbine maximum power output on large variations in system frequency (shown in Figure 2 as F(x)),
2. To make appropriate representation of the response of the HRSG, and
3. To represent the dynamics of the ST for long-term dynamic studies.

A detailed description of each of the model parameters, proper model usage, and example typical model parameters are provide for these models in the CIGRE TF document.

Figure 4 shows a simulation of a multi-shaft combined-cycle power plant using the generic models. The load/speed reference set-point of the gas turbine was injected with a step increase of 1.5% (0.015 pu). The simulation was performed using the model parameters presented in the document. The results show what would be the expected behavior of a typical combined-cycle power plant connected to a large power grid where system frequency would remain effectively unchanged due to such a step increase in the plant output. The gas turbine output increases until it is limited by the temperature control loop, transiently over-shooting its steady-state maximum power limit. The steam turbine, being essentially in sliding pressure mode, follows the gas turbine output with a delay of several minutes.

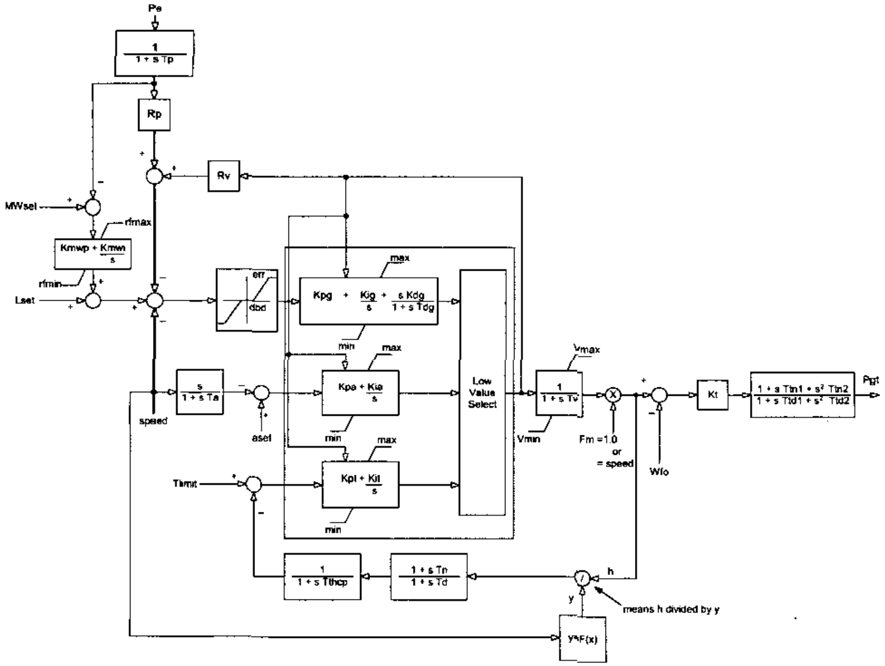


Figure 2: Proposed generic gas turbine model.

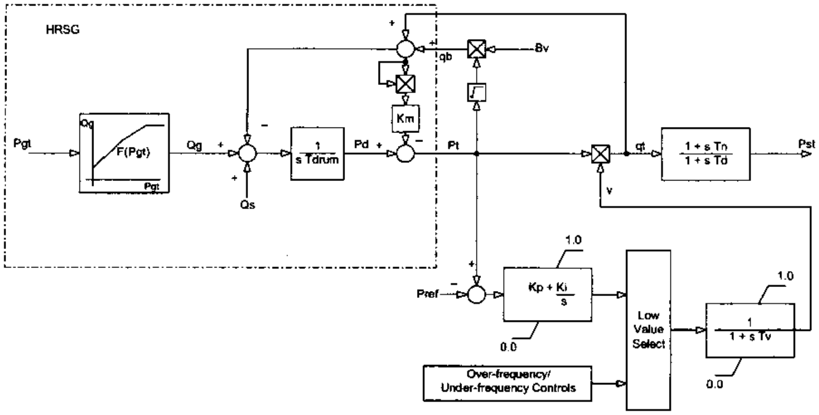


Figure 3: Proposed generic steam turbine model.

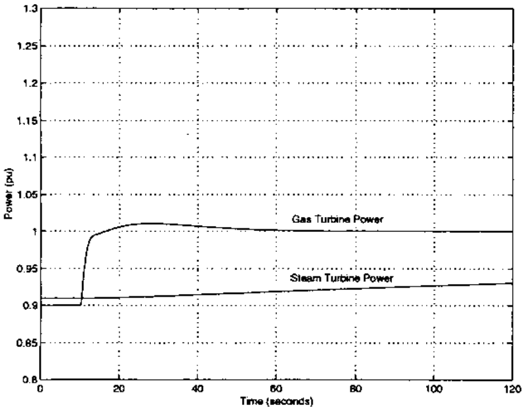


Figure 4: Simulated response of a multi-shaft combined-cycle power plant to a step-change in gas turbine power reference.

V. MODEL ASSESSMENT

The model assessment chapter discusses the testing work needed in combined cycle plants to meet three separate but related sets of objectives, as follows:

1. Testing to meet grid interconnection code and licensing requirements
2. Testing to identify characteristics of the plant that are needed to set up modeling parameters
3. Testing to verify that plant models are correct and appropriately accurate

It should be recognized that the testing discussed is far from the complete range of test work that will be done in the start-up and commissioning of a new plant and that there will be valuable carry-over of results from other testing. It is recognized with equal force that the testing done for other purposes is mostly oriented towards the internal operational requirements of the plant itself, while the testing discussed in the document is primarily oriented towards describing the plant as it will be seen from the perspective of the power grid. Testing oriented to the direct operation of the plant, particularly to its safety and efficiency, always takes precedence over the 'descriptive' testing discussed in the CIGRE document. Nevertheless, it is generally advantageous to introduce consideration of this descriptive test work into test planning as early as possible, both to ensure that its requirements are not missed out, and because there are often opportunities for advantageous coordination in the scheduling of the different testing requirements.

VI. SUMMARY AND RECOMMENDATIONS

Based on the contents of the CIGRE TF 38.02.25 Technical Brochure, the following recommendations are presented as guidance for the purpose of modeling combined-cycle power plants in power system studies:

- **Transient and mid-term time-domain stability analysis:** Transient stability analysis typically requires 5 to 20 second time domain simulations. The objective of such analysis is to study the dynamic behavior of the system following a large disturbance and thus identify if any generating systems become unstable due to first-swing instability. For the sake of simplicity it is adequate to use a simple gas turbine model without representation of fluctuations in maximum power output due to frequency variations and to represent the steam turbine with constant mechanical power. Simple gas turbine models exist in most commercially available power system simulation programs. Alternatively, the model presented in Chapter 4 of the CIGRE document (shown in Figure 2 & 3 of this paper) may be used. Mid-term time-domain stability studies require simulations over several minutes following a system disturbance. These simulations are often performed in relation to voltage-stability. If such studies involve disturbances that result in generation/load unbalance, then models of the form presented in the document (and shown here in Figure 2 & 3) may be used to represent both the expected response of the gas turbine and the steam turbine.

- **Small-signal analysis:** Small-signal stability analysis is typically performed on a set of the power system equations linearized at a specific operating condition. Inherent in the analysis technique is the assumption that system perturbations are small and thus should not invoke any non-linearities in the system. If the gas turbine is on temperature limit (base loaded), then small perturbations in electrical power and or system frequency will most likely have little to no effect on the output of either the gas turbine or steam turbine. Thus, it is appropriate for such cases to make no representation for either the gas or steam turbine-governor; that is, mechanical power is kept constant. Under part-load conditions a linearized version of a simple gas turbine model may be used. Since the steam turbine is most likely in sliding pressure mode, constant mechanical power input should be assumed for the steam turbine.

- **Islanding studies or studies on small systems:** Islanding studies are concerned with the separation of pockets of load/generation from a major power grid. This may occur as a result of the loss of a tie line between an industrial facility and a utility grid or as a result of a major disturbance that leave a large interconnected grid in fragments following major transmission line outages. Under such conditions the resulting islands may experience a large mismatch between generation and load. For such studies, particularly if the frequency in the island declines due to a lack of generation, models with adequate representation of the frequency dependency of the gas turbine maximum power output should be used. For mid-term simulations the output of the steam turbine must be linked to the gas turbine(s) through an appropriate steam turbine/HRSG model.
- **Plant specific studies:** Where studies are focused on the performance of a particular plant or the simulation of a specific test of a unit with measurement of internal plant variables, a more detailed model may need to be used and the advice of the manufacturer or other experts should be sought.

The generic models described in the document (and shown here in Figure 2 & 3), if used properly, are suitable for the studies described in the first three items. Other models of this type may be available in simulation programs. Other manufacturer specific models may be used to facilitate the objectives of a study of the nature described in the fourth bullet.

Because most grid studies involve broad assumptions regarding load behavior and day-to-day operational details of power plants, greater detail in the modeling of the plants does not necessarily improve the accuracy of the grid simulation. Rather than increasing the complexity of the plant models, it may be far better to use models of the simple and generic form presented in the document with care being taken to properly represent the expected behavior of each unit. Questions to be considered include:

- Are units partially loaded and thus able to respond to an increase in megawatt demand due to a decrease in system frequency?
- Are units base loaded or at their peak load (on temperature limit for gas turbines) or are they under outer-loop megawatt control (see Figure 4-1, constants Kmwp & Kmwi))?
- Has the response of steam turbines in combined-cycle power plants been properly modeled?

Ensuring that such questions have been answered and valid assumptions have been employed in preparing system models for grid studies are essential to the success of a study.

VII. ACKNOWLEDGMENT

Material for this paper was taken from contributions to the Task Force 38.02.25 Technical Brochure by P. Pourbeik (USA); R. Boyer (USA); K. Chan (SWITZERLAND); J. Feltes (USA); and J. M. Undrill (USA).

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Pouyan Pourbeik received the degree of BE in Electrical & Electronic Engineering and the PhD in Electrical Engineering from the University of Adelaide, Australia in 1993 and 1997, respectively. From 1997 to 2000 he was with GE Power Systems where most of his work was in the areas of transmission studies, power plant field testing and model development, development of new models for combined-cycle power plants and studies related to overvoltage protection of series capacitors on transmission lines. In September 2000 he joined the Consulting Business Unit of ABB Inc., where he is presently a principal consultant. He has most recently been involved in studies relating to voltage stability, interconnection of wind farms to utility grids, model development for SVC and HVDC systems and studies related to torsional interaction between transmission equipment and generating units. He presently chairs the CIGRE Task Force on modeling gas turbines and steam turbines in combined-cycle power plants and is the acting Secretary of the Power System Stability Subcommittee of the IEEE PES. He is a senior member of the IEEE and has authored/coauthored many papers on power system modeling and analysis.