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Start-up improvement of a supplementary-fired large combined-cycle power plant

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ABSTRACT

The start-up time of a combined-cycle power plant depends mainly on the heat recovery steam generator (HRSG) with its thick-walled tubes. This work contributes to a start-up time reduction of a large combined-cycle power plant (CCPP) with a supplementary-fired HRSG. Hence, a dynamic simulation model is developed using the advanced process simulation software (APROS). The flue gas path and the water/steam side are modelled in detail. All control structures required for the plant operation are implemented, e.g. drum, steam turbine bypass system and steam temperature control. The comparison between model predictions and design data at different load changes shows high correlation towards given data with an average relative error of 5%. Using the developed model, hot, warm and cold start-ups are simulated and finally three different reduced start-up times of gas turbine (15 min, 24 min and 38 min) are evaluated. A comparison between baseline and improved start-ups reveals time saving and fast power generation rate.

1. Introduction

Conventional thermal power plants are traditionally responsible for compensation of daily and seasonal load variations [1,2]. In many countries in Europe, the increased penetration of renewable energy sources in the generation of electrical power raises technical and economic challenges due to the uncertainty of supply and demand. Existing thermal power plants have to be retrofitted with optimised components and control circuits to improve their operation mode concerning load change times as well as rate of shutdown and start-up. In contrast to other thermal power plant, combined-cycle power plant (CCPP) is characterized by lower environment emissions, higher thermal efficiency and greater flexibility [3].

The modern concept of a CCPP is the result of an evolutionary process in the second half of last century. In the early stages of development, a gas turbine (GT) was installed to enhance the process efficiency of existing large-scale steam power plants by using the hot exhaust gas of GT for feedwater pre-heating instead of steam extractions or as a heat supply for pre-heating the combustion air. The Korneuburg power station (block A), commissioned 1960 in Austria, is considered the first attempt to combine a GT with a steam cycle. The idea was that the exhaust heat of a gas turbine can be absorbed by a heat recovery steam generator (HRSG), installed downstream in the flue gas path. The generated steam is used in a Rankine bottoming cycle, which generates additional power in the steam turbine (ST). The process efficiency of Korneuburg combined-cycle power plant did not exceed 32.5% [4]. At that time, the GT operating temperatures were as low as 620 °C at the turbine inlet and 310 °C at the turbine outlet, so that the supplementary firing of the HRSG was applied to support the steam cycle, as well as only simple single-pressure HRSG was used. Significant technological and economic developments have been achieved to improve the gas turbine performance, since. This includes high temperature resistant materials and thermal barrier coatings, low-NO_x combustion and innovative cooling methods. Furthermore, additional pressure stages were introduced over time in order to increase the steam parameters and to reduce the temperature mismatch between flue gas path and water/steam side. Today and according to the modern definition of the combined-cycle power plant, a

Abbreviations: APROS, Advanced Process Simulation Software; Attempt, attemperator; BFP, boiler feed pump; CCPP, combined cycle power plant; CRH, cold reheater; DC, device control; ECO, economizer; EVA, evaporator; FG, flue gas; FW, feed water; G, gain of PI; GT, gas turbine; HRSG, heat recovery steam generator; HP, high-pressure; HPBPCV1, high-pressure bypass to cold reheater; HPBPCV2, high-pressure bypass to condenser; MSIPCV, main steam to intermediate-pressure steam turbine control valve; IP, intermediate-pressure; LP, low-pressure; mem, memory; min, minimum; max, maximum; MSLPCV, main steam to low-pressure turbine control valve; LPBPCV, low-pressure bypass to condenser; MSHPCV, main steam to high-pressure steam turbine control valve; PI, proportional-integral controller; RH, reheater; RHBPCV, reheater bypass to condenser; SCR, selective catalytic reduction; SH, superheater; Select, selector; ST, steam turbine; t, integration time of PI.

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Nomenclatures

D	Diameter [m]
D_H	Hydraulic diameter [m]
E	Rate of entrainment [−]
F	Force per volume [N/m^3]
f	Friction factor [−]
g	Standard gravity [9.81 m/s^2]
h	static enthalpy [kJ/kg]Static enthalpy [kJ/kg]
h_0	Stagnation enthalpy [kJ/kg]
K	Heat transfer coefficient [W/m^{2}K]
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
p	Pressure [Pa]
q	Heat flow per volume [kW/m^3]
R	Rate of stratification [−]
T	Temperature [°C]
t	Time [s]
u	Velocity [m/s]
U	Internal energy [J]
z	Elevation [m]
χ	Volume fraction [−]
Γ	Mass transfer [kg/(m^{3}s)]
ρ	Density [kg/m^3]
Θ	Inclination angle [rad]

Subscripts

a	Annular flow
b	Bubbly flow
d	Droplet flow
form	Form loss
g	Gas phase
i	Interface between phases
k	Liquid or gas phase
l	Liquid phase
ns	Non-stratified flow
pu	Pump
sat	Saturated
st	Stratified flow
val	Valve
wal	Wall

1 + 1 arrangement of GT and ST units in combination with a triple-pressure reheat HRSG is state of the art. Supplementary firing of the HRSG is widely omitted due to the high temperature at the turbine outlet (in the order of 600 °C). Accordingly, the nominal process efficiency reaches up to 60% and plants with efficiency levels greater than 60% are now running, for example Irsching 4 power station that is located in Irsching, Germany [5].

In addition to its higher efficiency, combined-cycle power plant is also characterized by flexible unit dispatch. Fast response capability is a prerequisite for increasing shares of renewable feed-in from the renewable energy sources like wind power. Typically, there are three criteria to evaluate the practical flexibility of a thermal power plant: start-up time, maximum load gradient (positive and negative) and minimum load. A simple-cycle gas turbine needs only 20 min for starting, irrespective of its initial temperature [6]. However, the start-up time is limited by the thermal stresses in the thick-walled components of the heat recovery steam generator and the steam turbine, namely casing and rotor of the ST, high-pressure drum, outlet manifolds of final superheater and reheater of the HRSG. A modern combined-cycle power plant can sustain challenging load gradients up to ±60%/min, as e.g. stipulated by the Great Britain Grid Code for primary frequency response. The minimum load of a CCPP is mainly determined by the gas turbine, so that a stable combustion is achieved as well as CO and NO_x levels in compliance with emission regulations should be maintained. Typical gas turbines can run at a minimum load of 40–50% and this level may be further reduced to 20%, if a sequential-combustion design is applied. The minimum load limit is of high importance to flexible operation, since on the one hand it defines the lower boundary for negative load changes and on the other hand it reduces the number of start-ups and shutdowns.

Mathematical models contribute to a better understanding of the process and can play an important role for increasing the power plant efficiency and flexibility. Design and optimisation of thermal power plants start generally with steady-state modelling, where analyses of the thermodynamic properties of working fluid, mass and energy flows as well as process efficiency can be obtained for a series of operating points. The steady-state models do not require control structures and are mathematically based on mass, momentum, species and energy balances. The relevant next step is the process analysis with a dynamic simulation model. The latter presents an effective tool for assessing the control strategies, capabilities and the limitations when the operating system is close to the critical points [7]. Dynamic simulation is preferred for the proposal stage of the thermal power plant project, e.g. to check whether or not the load changes according to specific customer requirements are feasible without unacceptable lifetime consumption in thick-walled components. It is also a cost-efficient approach to support unit commissioning and regular operation by estimating component lifetime and directing maintenance. However, the investigation into the dynamic performance of thermal power plants requires besides the unsteady solution of conservation equations, the implementation of dynamic boundary conditions, the control structures and their associated components. Furthermore, several aspects such as the dynamic interaction between pressure circuits, the thermal inertia of the masses, the correct adjustment of control circuits and the restrictions due to warm-up of thick-walled tube (e.g. header, drum and steam turbine) for load changes as well as for cold, warm and hot start-ups must be considered carefully. The governing differential equations and the required numerical solver make the dynamic simulation codes very complex tools with long development periods.

For the transient modelling of thermal power plants, different process components such as pipe, heat exchanger, turbomachines, drum and valve etc. are required [8]. In addition to process components, a thermal power plant includes several automation and electrical systems. The control structures (automation system) consist of various components such as controllers, analogue and binary components, which are combined in order to satisfy certain control requirements [9]. The accurate description of control structures is essential in order to obtain a meaningful dynamic response. The consideration of electrical components in dynamic simulation of thermal power plants is of high relevance to calculate the electrical power consumption at base loads and make sure that other components get the needed electric power during transients. Furthermore, they are used to evaluate the effect of possible failures in the electrical network on automation and process components and to study the plant behaviour at severe break down cases such as blackout (i.e. electricity supply is lost).

When looking into the scientific literature, the steady-state modelling of combined-cycle power plants were frequently reported, considering plant simulation and optimisation, among others recently published works are [10–13]. Since the gas turbine is an inherently flexible component, the bulk of published works on dynamic simulation is dedicated to the modelling of the HRSG due to its considerable inertia and delayed system response. Detailed dynamic studies of load changes, shutdown and start-up procedures under thermal stress restraints transients are conducted, for