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Analysis of a simplified Steam Turbine governor model for power system stability studies

M. Pondini[a]*, A. Signorini[b], V. Colla[a], S. Barsali[c]

[a]Scuola Superiore Sant'Anna TeCIP Institute ICT-COISP Center, Via Moruzzi 1, Pisa (PI), 56124, Italy
[b]© 2018 BAKER HUGHES, a GE company, Via F. Matteucci 2, Firenze, 50127, Italy
[c]University of Pisa, Department of Energy and Systems Engineering, Largo Lucio Lazzarino 1, Pisa (PI), 56122, Italy

Abstract

The present study describes an analysis performed on a simplified Steam Turbine governor model, which is useful for pre-tuning the machine regulation system. A dynamic model has been implemented in two different simulation tools, namely DigSILENT PowerFactory and Matlab/Simulink, to the aim of verifying the suitability of the latter one for power system stability studies. The proposed work paves the way to the wide range of possibilities connected to the integration of the machine governor model with other simulation blocks of a Combined Cycle Plant, by enabling the opportunity for pre-commissioning of the regulation system together with the analysis of the fulfillment of grid code regulations.

Keywords: Steam Turbine; Governor; Dynamic model; Matlab; Digsilent.

Nomenclature

		HRSG	Heat Recovery Steam Generators
		PID	Proportional-Integral-Derivative
CPP	Combined-Cycle Plant	SP	Set point
GT	Gas Turbine	ST	Steam Turbine
HP	High Pressure	TSO	Transmission System Operators

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* Corresponding author. Tel.: +39-347-6216973; fax: +39-050-882564.
E-mail address: m.pondini@santannapisa.it.

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Introduction

The increasing penetration of renewable energy sources in the energy market requires traditional power production technologies to cope with an ever increasing unpredictability in the grids, as highlighted in [1]. The intermittent characteristic of renewables, in fact, determines grid frequency to change more dramatically, thus the compensation from other energy sources is required and needs to be verified with suitable simulation models [2]. This automatically translates into the need for a higher flexibility of traditional baseload units to be achieved through enhanced plant regulation capabilities, which normally should comply with the grid code of the specific country. Sourkounis et al. provided an overview on the main requirements specified in the grid codes [3], which should be verified through a simulation model of the power and speed/frequency control loops within the plant. In general, the level of complexity and the structure of the models enabling power system stability studies respects the standards established by the IEEE Power & Energy Society, whose task forces make recommendations on the applicability of these models for simulating turbine governors response with different levels of accuracy [4]. For instance, in [5] the evolution of these models is analyzed in detail together with the assumptions behind each version.

These models are typically translated into the most suitable simulation tools, which, in general, include also a detail of the grid layout. Depending on the specific scenario under analysis, the grid representation can be deeply simplified without disregarding any interaction between the power system and the grid. However, the common approach consists in performing even these types of simulations with tools which are usually dedicated and optimized for grid dynamic analysis, such as DigSILENT PowerFactory.

The relevance of this analysis comes from the role of Transmission System Operators (TSOs) that are entrusted with transporting energy and have the duty to ensure the security of supply and reliability of the system, as underlined in [3]. Therefore, when a new power plant connection to the grid is required, a preliminary verification of plant regulation capabilities in predefined dynamic scenarios becomes of upmost importance, by complying with the constraint of fulfilling the acceptance criteria imposed by the TSO. Moreover, these scenarios do not only impact the interaction between the power production and transmission systems, but also affect the operation of the whole power plant, whose dynamics should be taken into consideration as well. Normally this task is faced by the plant owner, not by the TSO's, and it is accomplished through simulation tools which are suitable for process system simulations, such as Matlab/Simulink. As a result, the verification of an equivalent performance from the two tools enables a complete overview around process dynamics as well, which can be further deepened by exploiting the most suitable simulation tool.

The aim of the present study is to analyze the performances of two different tools, DigSILENT and Matlab/Simulink, which are suitable, respectively, for grid and for process system dynamic simulations. This led to the opportunity of identifying and testing those scenarios for which a grid detailed model does not affect the accuracy of the results, and to the consequent adoption of Matlab/Simulink as a tool for further considerations around process dynamics.

The paper is organized as follows: Sec. 2 provides an overview on the Combined-Cycle Plant (CCP) case in power system stability studies, Sec. 3 presents the governor model to be translated into the two different simulation tools; Sec. 4 depicts the comparison between the two solutions. Finally, Sec. 5 provides some concluding remarks and hints for future work.

1. Power system stability: the Combined-Cycle Plant case

The analysis around power systems stability has always been a matter of concern in the literature, where different types of power plants have been investigated together with the simplified models of their components. In [5] a specific overview around turbine governors is provided; Eremia et al. also go through grid components modeling and describe the most common transient disturbances related to grid regulations [6]. When such analysis aims at achieving a smooth and controlled regulation of a power plant, CCPs represent one of the most critical cases due to the parallel and linked operation of both Gas Turbine (GT) and Steam Turbine (ST). Figure 1 shows the typical layout of a CCP with a so-called "2-2-1" arrangement (2 GTs, 2 Heat Recovery Steam Generators (HRSGs) and 1 ST), where load control is active on both GT and ST. As depicted from this simplified schematic diagram, the controller acts on ST control valve to adjust the output power from the ST and simultaneously regulates the GTs load by throttling the fuel admission valve. The quality of the steam generated within the boiler depends on the operation of the GT, thus the steam process regulation must deal with variable exhaust gases resulting from the GT partialization dictated by a specific scenario. Therefore, the capability of evaluating the consequences that different scenarios have on steam pressure and temperature at the inlet of the ST is of utmost importance. With this feature the action on ST control valve can be balanced between the load controller Set Point (SP) and the regulation of a steam process parameter, e.g. the steam inlet header pressure, as represented in Figure 1. The gap to be filled in order to achieve this goal is represented by the integration of the turbine governor model with a simplified model of the boiler and the steam inlet header dynamics.

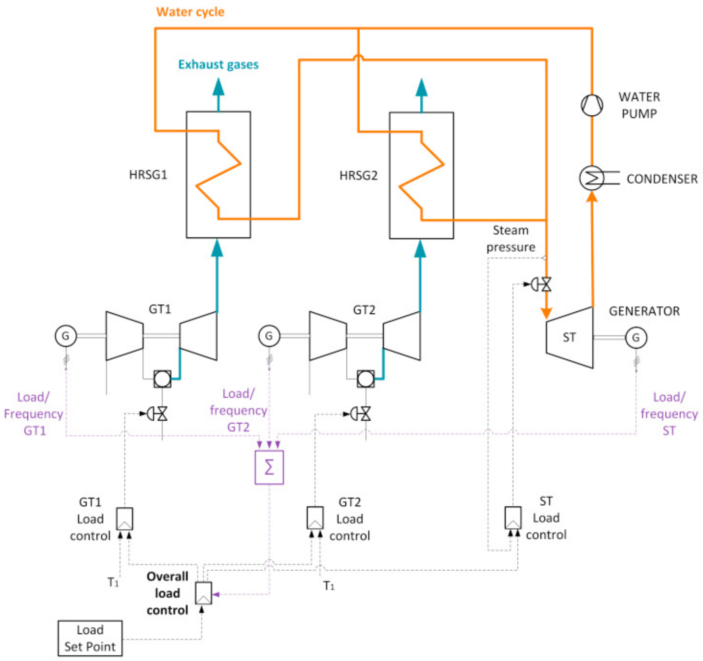
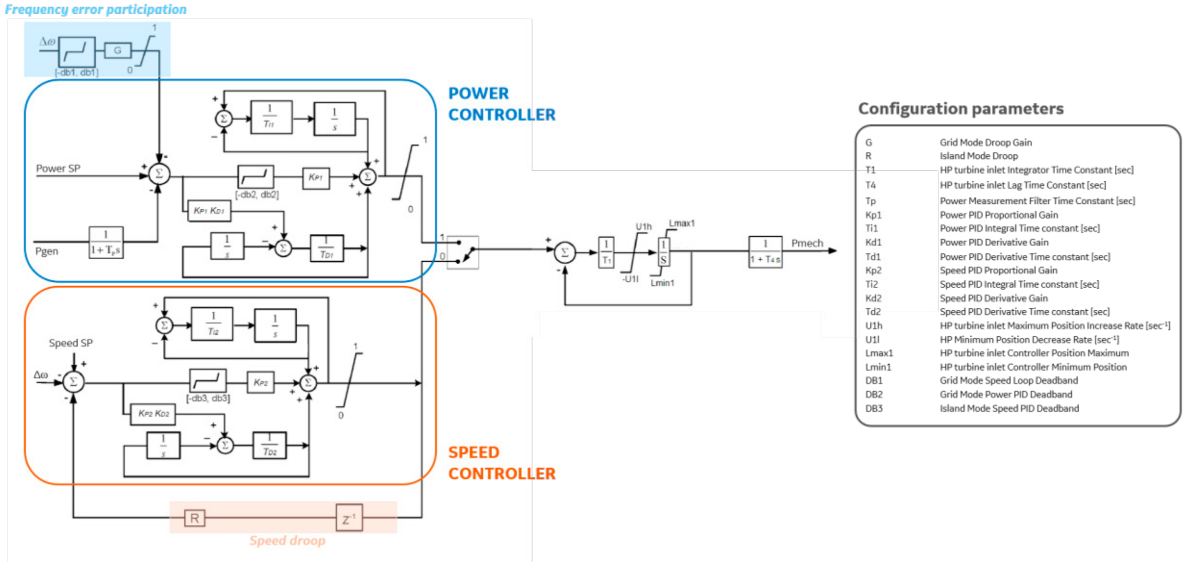


Fig. 1. Combined-Cycle load control system layout (T_1 = Limit for GT inlet temperature)

Extensive research has been performed around GT models in power system stability studies [7]; starting from Rowen's model for heavy-duty GTs [8], different versions have been developed by adding further details to the machine regulation layout. The applicability limits coming from the assumptions behind each model have been aligned with the dynamic scenarios that can be simulated, namely load rejection and load steps with a limited load change percentage. A similar analysis on IEEE ST governor model applicability limits is necessary in order to verify the regulator functionalities before commissioning procedure. The simplified version of this governor, according to the IEEE standards, consists of two PID loops regulating respectively power and speed [5] and through this model both the machine connection with a prevalent grid and the operation in an islanded system can be simulated. Moreover, the opportunity of integrating the loop of inlet steam pressure regulation together with the dynamics of the boiler upstream enables an overview of the whole process, including GT operation characteristic.

2. The ST governor model

Starting from a detailed literature review on turbine governor models for the specific case of CCPs, as described in [4], and for other type of applications [5], a customized ST governor model for power system stability analysis has been identified (see Figure 2). The model is structured according to the capability of simulating the machine regulation in both island mode and when connected to the national grid system. In the former case the speed controller loop, namely the ST control valve, which is represented on the right side of the diagram, acts in order to maintain a constant speed/frequency of the islanded system. In this situation, if an additional load is connected to the plant grid, it causes an unbalance from the generated power and the actual consumption. In other words, the steam currently expanding through the ST is not sufficient to keep the same speed ($\Delta\omega \neq 0$), thus the speed regulation system further opens the ST control valve. In the latter case, when the power plant feeds the national grid but it does not actually determine its speed/frequency alone, the regulation switches to power controller mode and the speed is fixed by the grid. With the same goal of reaching a balance between production and consumption to maintain the frequency of the grid typically at 50 ± 2 Hz, the grid operator can request a different contribution from each power plant according to its capability of regulating the grid frequency by adjusting its power production. This feature is called droop regulation and it comes into play when the frequency deviation is higher than a certain limit, it is then represented with a dead-band and a gain value adding up to the error respect to the load SP. Both the speed and power loops are represented as a Proportional-Integral-Derivative (PID) controller where the derivative contribute is normally set to 0. The configuration parameters of the control loops, which are described in Figure 2, determine the response of the system and need to be tuned according to the required regulation performances. The command coming from either of the two acts on the throttling of the control valve system, which, in this case, is represented as the single contribute of the High Pressure (HP) section of the ST. In general, the ST is divided into two different sections, each one with a dedicated control valve system contributing to the speed or power regulation. The interaction of the two valves in the control loop needs the best tuning and valve coupling architecture.



Configuration parameters

G	Grid Mode Droop Gain
R	Island Mode Droop
T1	HP turbine inlet Integrator Time Constant [sec]
T4	HP turbine inlet Lag Time Constant [sec]
Tp	Power Measurement Filter Time Constant [sec]
Kp1	Power PID Proportional Gain
Ti1	Power PID Integral Time constant [sec]
Kd1	Power PID Derivative Gain
Td1	Power PID Derivative Time constant [sec]
Kp2	Speed PID Proportional Gain
Ti2	Speed PID Integral Time constant [sec]
Kd2	Speed PID Derivative Gain
Td2	Speed PID Derivative Time constant [sec]
U1h	HP turbine inlet Maximum Position Increase Rate [sec^{-1}]
U1l	HP Minimum Position Decrease Rate [sec^{-1}]
Lmax1	HP turbine inlet Controller Position Maximum
Lmin1	HP turbine inlet Controller Minimum Position
DB1	Grid Mode Speed Loop Deadband
DB2	Grid Mode Power PID Deadband
DB3	Island Mode Speed PID Deadband

Fig. 2. IEEE ST governor model layout and configuration parameters

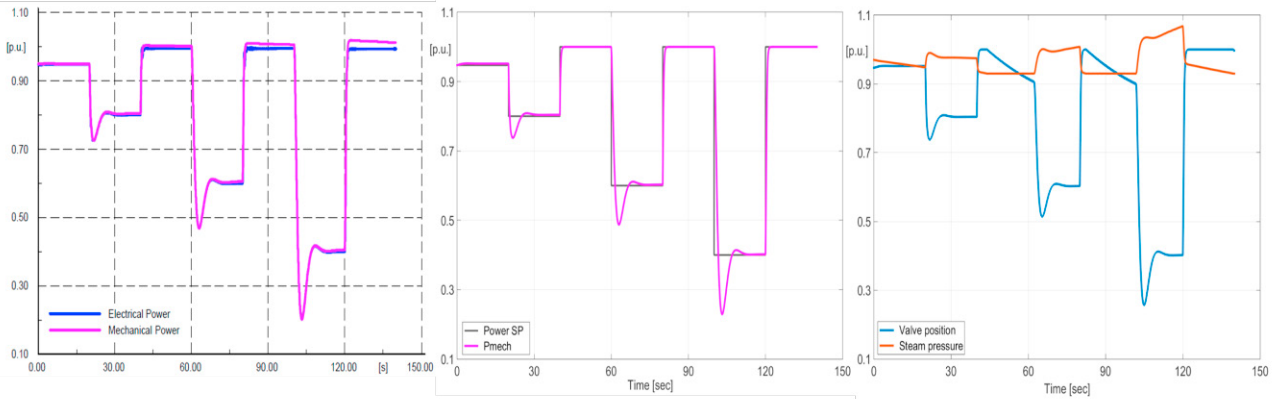
Thus, within the first part of the present study the simplification of a single valve with constant steam pressure upstream has been adopted; a deeper investigation around control valve system layout and tuning is currently being pursued as part of the ongoing research activity as well as the integration of the steam pressure variability and correspondent control loop, whose preliminary results are shown.

The HP regulation system is represented with a time constant integrator and a limited integrator accounting for the response of the actuation system of the valve, where the closed loop has the function of the servo-controller. Through a lag time constant the steam expansion in the ST is taken into account and the final output of the model accounting for the mechanical power produced is calculated. This value is fed back to the model as *Pgen* after applying the efficiency of the generator.

3. Test comparison results

The model described in Section 2 has been translated in both DigSILENT and Matlab/Simulink and configured according to the parameters of a CCP project with a single HP ST section. This power train consists of a ST with gearbox and generator, whose inertial contributes are considered in the torque balance determining the speed of the train. A study has been conducted to the aim of verifying the stability of the generating set against transient conditions: in order to compare the performances of the two modeling tools a simulation of some generating active power steps (power increment and power decrement) with the generator connected in parallel to the main grid has been carried out. By varying the power SP of the ST generation train with different load steps, the power loop intervenes and adjusts the ST control valve stroke in order to meet the load required. Figures 3.a and 3.b show the results of the comparison of the ST governor response when implemented in the two different simulation environments. The aim of this test is to demonstrate the feasibility of performing an accurate power system stability analysis even with a simulation tool which is not specifically dedicated to grid simulations. A preliminary analysis of the results shows that the behavior of the ST governor is equivalent in the two cases; its response, in fact, is depicted by the mechanical power trends (in magenta color in Figures 3.a and 3.b), which are replied in the two graphs with an accuracy within acceptable limits. As we may have already expected, the amplitude of the overshoots increases with higher step loads demanded by the power SP (*Power SP*), and this is correctly replied in both cases. This feature can be considered, together with the response time for each power step, a good validation requirement for an accurate comparison of the two simulation tools.

Thus, the results presented are satisfying enough to justify the deployment of Matlab/Simulink in power system stability studies. In addition, Figure 3.c depicts the same test described above with an inlet steam pressure PI controller also integrated, where a simplified representation of the steam header and boiler dynamics provides the calculation of steam pressure variations according to control valve throttling. In this enhanced version of the model the switch between load control to pressure control occurs when the steam pressure value drops below 0.93 in per unit (p.u.) and valve starts closing to restore stable conditions. This can be noticed by looking at the valve position trend in blue which, after the step opening phase, shows a more unstable behavior due to the continuous switch between load and pressure control to restore pressure above the limit.



(a) (b) (c)

Fig. 3. Results of ST governor response tests with different active power step demands performed in DigSILENT (a) and Matlab/Simulink respectively without (b) and with (c) PI pressure controller integrated.

These additional results justify the focus around Matlab/Simulink environment and demonstrate the possibility of integrating other complementary simulation blocks in order to better understand the dynamics of the steam process around the machine and tune the control parameters. In particular, such environment gives the additional benefit of substituting the simplified controller (PI) with the actual turbine governor architecture which is applied on real unit control system, by thus allowing testing and tuning of the real governor parameters which determine the overall system response. In order to further demonstrate the feasibility of this approach, an island grid test will also be conducted and additional comparative analyses of the results achieved will be integrated.

The validation of the approach of using Matlab/Simulink for the simulation of dynamic scenarios in which the grid system can be deeply simplified will represent a strong basis for spending additional efforts in the implementation of the actual governor architecture. The final goal of the present research activity is to give evidence of the results of different test cases conducted with such architecture implemented, which will enable the analysis of additional dynamic features that are currently disregarded and the creation of a simulation environment for control parameters pre-tuning.

4. Conclusions

The study presented is part of a research activity, which aims at investigating the CCPs dynamic behavior when facing transient conditions coming from national grid disturbances or plant grid load unbalance. There is a strong focus around grid reliability due to the increasing penetration of renewable energy sources. Therefore, the analysis of power systems stability becomes a primary requirement in order to ensure the plant compliance with national grid code requirements. The most suitable tool for this type of studies is a simulation system, which is capable of considering the transient phenomena occurring within the power plant when interacting with the grid system.

The results achieved in this preliminary phase of the study represent a strong basis for the further development of the model, which will continue with the improvement of the representation of the boiler dynamics through a high-fidelity model and of the steam process upstream the ST governor. In this way the steam pressure control loop can be further adjusted in order to limit the negative impact that a ‘blind’ simulation respect to the steam conditions control can have on the ST control valve regulation. Furthermore, the opportunity of substituting the simplified power/speed loops with a carbon copy of the real ST governor to tune at site will enable a dedicated analysis on the job and, consequently, a strong pre-commissioning procedure for parameters tuning. A complementary study will also deal with the regulation of HP and Low Pressure sections of the ST power train in order to cover the analysis of the interaction between the two control valves.

Future work will be in line with the alignment to national grid code requirements, which are a matter of high relevance especially for TSOs.

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