Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Models of control valve and actuation system for dynamics analysis of steam turbines ☆

Maddalena Pondini [a,*], Valentina Colla [a], Annamaria Signorini [b]

[a] Scuola Superiore Sant'Anna, TeCIP Institute ICT-COISP Center, Via Alamanni 13B, 56010 Ghezzano, Pisa, Italy
[b] © 2016 General Electric Oil & Gas Inc., Via F. Matteucci 2, Firenze 50127, Italy

HIGHLIGHTS

- A dynamic model of Steam Turbine control valve and actuation systems is proposed.
- An innovative study of the equations that rule the assembly movement is provided.
- Control valve response and accuracy is analyzed in detail with test and simulation.
- System upgrade is achieved with Electro-Hydrostatic Actuation technology.

ARTICLE INFO

Article history:
Received 23 January 2017
Received in revised form 20 April 2017
Accepted 14 May 2017
Available online xxxx

Keywords:
Dynamic model
Steam turbine
Control valve system
Matlab

ABSTRACT

The paper describes a study conducted on the control valve and the actuation systems of a Steam Turbine. These devices are of utmost importance, as they rule the machine final power production and rotational speed, thus their accurate modelling is fundamental for a valuable dynamic analysis of the whole system. In particular, a dynamic model developed in the Matlab/Simulink environment is proposed, which supports the analysis of the operational stability of the hydro-mechanical system as well as the failure modes that it may face during operation. The model has been successfully validated through specific field tests conducted on the actuation system at a cogeneration plant located in the General Electric Oil & Gas - Nuovo Pignone facility of Florence. The proposed work also highlights the requirements that new actuation technologies should fulfill in order to meet control valve system performance criteria and is thus useful as both a methodological approach and a "virtual benchmark" allowing to validate in advance any new actuation system.

1. Introduction

Nowadays in any industrial sector a continuous and rapid evolution is observed towards ever more demanding applications and intelligent solutions aimed at enhancing production flexibility and efficiency while reducing wastes as well as resources and energy consumptions. As a consequence, the need of deploying updated technologies and practices arises, especially for those applications that are highly energy dependent. A constant research and investigation effort towards up-to-date technologies is required in order to keep a high level of competitiveness in the market. It is in this environment that the concepts of advanced control, performance degradation monitoring and diagnostics came along, meeting the main criticalities that are faced in the industrial field so far. Vanraj et al. applied these concepts in the prevention of machine unavailability and breakdown maintenance due to vibration related problems [1]; a similar approach has also been adopted in Ref. [2], where Agudelo et al. integrated more developed techniques for fault detection and troubleshooting. Moreover, the advent of the digital power together with all the capabilities related to big-data analytics, 'digital twins', Model Predictive Control (MPC) and Artificial Intelligence (AI) enables a completely new approach to face the challenge of continuous performances improvement. This scenario represents a big opportunity for the industrial world to drive productivity and efficiency when coping with a really uncertain background, as highlighted in [3]. A further relevant example in this framework is provided by Venkatasubramanian et al. [4], who analyzed and compared different diagnostic methods, namely quantitative model-based methods, qualitative methods and pro-

---

☆ The short version of the paper was presented at ICAE2016 on Oct 8-11, Beijing, China. This paper is a substantial extension of the short version of the conference paper.

* Corresponding author.

E-mail addresses: m.pondini@sssup.it (M. Pondini), colla@sssup.it (V. Colla), annamaria.signorini@ge.com (A. Signorini).

http://dx.doi.org/10.1016/j.apenergy.2017.05.117
0306-2619/© 2017 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Pondini M et al. Models of control valve and actuation system for dynamics analysis of steam turbines. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.05.117

Nomenclature

Abbreviations

AI	Artificial Intelligence
CPC	Current to Pressure Converter
CSP	Concentrated Solar Plant
EHA	Electro-Hydrostatic Actuation
GE O&G	General Electric Oil & Gas
GTCC	Gas Turbine Combined Cycle
HP	High Pressure
I/H	Current to Hydraulic pressure
ISCC	Integrated Solar Combined Cycle
LP	Low Pressure
LNG	Liquefied Natural Gas
LVDT	Linear Variable Differential Transformer
MPC	Model Predictive Control
ST	Steam Turbine

Parameters

P_{sec}	secondary oil pressure [bar]
A	servo-cylinder spool area [m^2]
K	servo-cylinder spring stiffness [N/m]
$x_{0,servo}$	servo-cylinder spring pre-compression [m]
M_{servo}	servo-cylinder spool mass [kg]
$\boldsymbol{\sigma}$	servo-cylinder spring damping coefficient [N s/m]
G	lever center of mass
O	lever center of rotation
p_1	lower chamber pressure [bar]
p_2	upper chamber pressure [bar]
A_1	lower chamber area [m^2]
A_2	upper chamber area [m^2]
p_{atm}	atmospheric pressure [bar]
A_{rod}	rod cross sectional area [m^2]
M	mass of moving parts at cylinder rod [kg]
$\boldsymbol{\sigma}_{cyl}$	cylinder damping coefficient [N s/m]
F_{load}	load force at the actuator rod [N]
F_r	cylinder friction [N]
J_G	inertial torque of the center of mass [kg m^2]
M_{lever}	lever mass [kg]

Variables

$x_{spring,servo}$	servo-cylinder spring position [m]
s	laplace variable
y	piston position [m]
θ	rotation angle [rad]

Functions

x	servo-cylinder position [m]
F_{cyl}	cylinder force [N]
M_0	total torque coming from acting forces [N·m]
M_{in}	torque of inertia [N·m]
R_{in}	force of inertia [N]

cess history-based ones in order to underline the advantages connected to early detection and diagnosis of process faults.

In addition to facing uncertainties and challenges connected to the need of achieving and/or preserving competitiveness and technological leadership within the global market, which is common to all the industrial sectors worldwide, the energy sector has to deal with a further factor enhancing the complexity of any control task, which is related to the increasing share of renewable power production with its characteristic of exploiting an intermittent energy source. This is the case of solar plants and wind farms, where the availability of the primary source determines the operation of the entire plant and its unbalancing contribute to the grid. Previous research dealt with wind and solar output variability by introducing an optimal market share estimation for both the energy sources [5], other studies approached this uncertain characteristic through a forecasting methodology applied to an isolated microgrid where flexible load management improved the economic dispatch [6]. Providing an adaptive approach to the control of the system operation can also allow dealing with this element of variability, which is challenging from a components safety perspective too. Camacho et al. provided examples of successful applications of control for different energy sources, reinforcing the possibility of achieving more complex and efficient designs while at the same time maximizing the exploitation of the availability of the energy source [7]. For instance, in [8] MPC was applied to optimize the generation scheduling in Concentrated Solar Plants (CSP) in order to both track the schedule which was committed for the ongoing day on the basis of the most recent electricity price and weather forecast and to generate the schedule for the following day.

Together with an optimization on the control perspective, industrial systems in general always have to deal with incoming technological innovation, which brings reliability, efficiency and cost-saving opportunities to all the process levels. It is only thanks to a continuous research and upgrade that process industries will be able to demonstrate their flexibility. System upgrading is the requirement behind the fulfillment of performance, reliability and system simplification that are the main drivers of competitiveness in the industrial field. In literature many examples of beneficial upgrades are presented, either from an environmental stand point, such as discussed in an interesting exemplar industrial case in [9], or from a control perspective, where automation and simplification led to operational and economical benefits, such as proposed by Edwards in the case of a hydropower plant [10], or from a technological perspective, as described by Madisetti et al. in [11]. In this last study a new infrastructure of developing automation tools is proposed to reduce the cost of the re-design of obsolete components. The driver that usually pushes towards system upgrading is simplification, which, in most of the cases, comes together with higher reliability and reduced costs. A suitable example in the oil and gas field is the historical presence of auxiliary systems fed by high quantities of oil and bringing the necessity of installing inter-connecting piping and oil tanks. Hydraulic or pneumatic control units, for example, are usually applied within mechatronic systems where operational and functional safety is the main requirement, as underlined in [12]. Consequently, maintenance and safety requirements as well as system complexity are leading customers towards oil-free solutions, or electric systems with reduced oil quantities, where failure modes, such as wear fault problems, have been studied in depth in the literature [13]. The same importance should be given to the risk associated with the specific failure causes, which requires a prioritization based on the system, product or service affected [14].

In particular, in the power production field, Steam Turbine (ST) dynamics are of upmost importance especially when coping with the renewable energies uncertain characteristic. Due to the periodic nature of solar radiation, which demands for an adaptation of the modelling and control approaches conventionally adopted in the power generation field, solar thermal power plants are often subjected to transient conditions, such as discussed, for instance, in [15]. Even so, the technologies subdued to this type of energy source present many advantages in terms of performances and electricity costs, as underlined in [16], and represent a valid alternative to fossil fuels from both conversion efficiency and environmental impact point of view [17]. Similar findings also come from

Please cite this article in press as: Pondini M et al. Models of control valve and actuation system for dynamics analysis of steam turbines. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.05.117