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Steam Turbine control valve and actuation system modeling for dynamics analysis

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Abstract

The paper describes a study conducted on Steam Turbine control valve and actuation systems, which rule the machine final power production and rotational speed. A dynamic model developed in the Matlab/Simulink environment is proposed to support 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 was validated through specific field tests conducted on the actuation system at a cogeneration plant in Nuovo Pignone, Florence. The proposed work also underlines the requirements that new actuation technologies should fulfil in order to meet control valve system performance criteria.

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Keywords: Dynamic model; Steam Turbine; Control valve system; Matlab.

1. Introduction

In Steam Turbine (ST) control and actuation, the steam control valve plays a key role in two main areas:

- *Operability*, as it drives the turbine ability to cope with sudden load variations and allows to accurately control turbine speed when running at no load conditions [1];
- *Reliability*, as the traditional oil actuation systems that rule the valve movement can be subjected to functional deterioration due to oil contamination or presence of impurities [1].

The ST regulation system is mainly composed of an actuation system connected to a mechanical assembly that transmits the motion to a series of shutters, whose purpose is to enable the steam flow passage into the machine. The goal of the regulation system is primarily to vary the quantity of steam

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delivered to the ST to compensate the variation of the turbine train conditions. The ST industry has a long tradition of Low Pressure (LP) and High Pressure (HP) actuation systems, which have been improved over the years based on field experiences. Power generation applications require higher response capability, due to the need to cope with grid load rejection, which implies the capability to control the speed variation within over-speed limits. In addition, in the ever growing context of renewable plants (i.e. Concentrated Solar Plants), STs are exposed to sudden steam conditions variations which can challenge the traditional actuation system dynamics capability and even lead them, in the worst cases, to instability [2]. Therefore, high responsiveness of the control valve system is of utmost importance in order to improve the operation stability.

Due to the aforementioned challenges, a wide research on possible solutions for the actuation systems led to a comprehensive comparison of three different technologies for General Electric Oil & Gas (GE O&G) ST-applications: LP, HP and, most lately, Electro-Hydrostatic Actuation (EHA) systems. In this paper a specific comparison between an LP and an EHA system is proposed, while the need for improved ST stability margins comes along with the priority of a model-based approach, which is the main focus of the present work. This implies the additional capability of enabling the study of how a performing actuation affects the response of the system downstream in terms of stability and precision which are key factors for an optimized operation of the whole regulating chain.

The paper is organized as follows: Sec. 2 provides an overview on control valve system main features and requirements, Sec. 3 presents the so-called ‘legacy actuation system’ and the simulation model structure of the control valve system with this specific actuation solution; Sec. 4 depicts the model validation results and compares two different actuation technologies. Finally, Sec. 5 provides some concluding remarks and hints for future work.

2. The control valve system

Inlet control valves performances have always been a matter of concern in the literature, extensive research led to improved valve designs in order to deal with high pressures and temperatures [3] as well as steam flow instability around the valve [4]. Their non-linearity characteristic has also been addressed providing solutions for compensation of the phenomena [5]. In addition to these important features, ST control valve actuation systems also need to be reliable and high-performing when the overall control loop of the ST has stringent requirements in terms of fast response to a change in actual condition. Nevertheless, even for systems where the reaction time requirement is not so tight, the actuation system plays a fundamental role in the control loop. Until now a dynamic model of the whole regulating chain was not needed, since the overall control loop is adjusting on the ST power production output, therefore controlling the actuator position on the requirements of the entire loop. The purpose of this work is to meet the necessities connected to the achievement of a better performing governor, which consequently implies the need for a predictive model of the control valve system. Such model also enables an analysis aimed at identifying the elements of the entire chain that may represent a ‘bottleneck’ for the control loop. In particular, a modelled control valve system allows the study of the effect of the failure modes of the actuation system, when coupled to the turbine governor, and, finally, the definition of the best recovery actions to be taken by the turbine governor logic.

The actuation system considered in the present work, that is referred in the following as ‘legacy system’ for sake of brevity and is represented in Fig. 1.a, operates within low oil pressure ranges in the cylinder chambers: for this reason the whole control oil circuit is named *LP control oil*. Fig. 1.b. shows the LP control oil system with the control valve assembly simulation model layout, where the main components of the entire control loop are represented.

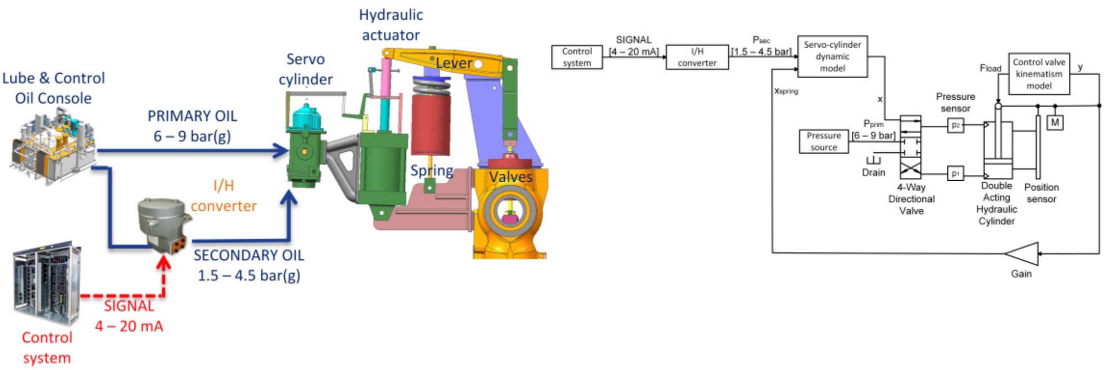


Fig. 1. (a) Legacy actuation system with control valve assembly; (b) Simulation model layout

3. Legacy actuation system and control valve model structure description

The operation of this particular actuation system is based on the supply of oil coming from the lube and control oil console, whose structure is not included in the model, being its analysis out of the scope of the present work. Since primary oil is supplied at constant pressure by the oil console, a pressure source is applied as a simplification in the model. The oil coming from the lube and control oil console header plays an important role for this type of actuation system, since it both moves a spool inside the servo-cylinder connected to the actuator (secondary oil) and enters the hydraulic actuator chambers (primary oil). The secondary oil pressure is set by the I/H converter, that translates a current command signal (4-20 mA) into oil pressure. The 4-20 mA command derives directly from the control system and corresponds, respectively, to the valve closed and opened positions. The motion of the spool in the servo-cylinder is regulated by the secondary oil: it alternatively opens the connection orifices that let the primary oil flow either in the upper or in the lower chamber of the hydraulic cylinder. A lever transmits the actuator movement directly to the valves with the help of a spring, whose primary function is to keep the valve closed in case of a hydraulic actuator failure. The final goal of this mechanical system is to regulate the steam passage through the valve, by lifting up a valve guide that opens in sequence four or five shutters, which in turn feed different sections of the machine and realize a fine regulation.

The structure of the model, which is developed in the Matlab/Simulink simulation environment and is depicted in Fig. 1.b, follows the layout of a typical LP control oil system and is articulated into different blocks representing the main components of the system: I/H converter, Servo-cylinder, Hydraulic Actuator and Valve system. The SimHydraulics toolbox was applied for hydraulic subsystem modelling [6]. The input of the model is the valve command signal which is transformed into the secondary oil pressure signal through the electronics implemented by the I/H converter. Such pressure controls the servo-cylinder spool, which is kept in neutral position by the action of an embedded spring when the secondary oil pressure is at 1.5 barG. This type of valve can be simulated using the 4-Way Directional Valve Simscape block whose dynamics can be obtained from the following equation which, according to the Laplace transform, describes the servo-cylinder position:

$$x = \frac{P_{\sec} A - K(x_{0,servo} - x_{spring,servo})}{M_{servo} s^2 + \sigma s + K} \tag{1}$$

where $P_{sec}A$ is the secondary oil pressure acting on the servo-cylinder spool, $Kx_{0,servo}$ is the spring preload and $Kx_{spring,servo}$ represents the leverism mechanic retroaction. Two physical signals connect the 4-Way

Directional Valve to the hydraulic cylinder chambers, modeled with a Double-Acting Cylinder Simscape block, which generates a force signal according to the load applied at its rod. In order to determine the value of the load at the actuator rod an equilibrium of torques was implemented considering the rotation of the system around the fulcrum of the lever, thanks to this approach the inertia of the lever is also taken into account. The equilibrium of torques for this dynamic system is computed as follows:

$$\vec{M}_0 + \vec{M}_{in} + (G - O) \wedge \vec{R}_{in} \tag{2}$$

where M_0 is the total torque coming from acting forces, M_{in} is the torque of inertia, R_{in} is the force of inertia, and $G–O$ is the distance between the fulcrum and center of gravity.

The model is able to calculate the position and speed of the actuator rod as a result of the dynamic response of every component simulated, this signal is directly related to the valve lift and thus to the steam flow entering the steam turbine. Cylinder chambers pressures can also be retrieved from the simulation in order to calculate the actuation system force generated as per equation below [7]:

$$F_{cyl} = p_1 A_1 - p_2 A_2 - p_{atm} A_{rod} = M\ddot{y} + \sigma_{cyl}\dot{y} + F_{load} + F_r \tag{3}$$

where p_1, p_2 are the pressures in cylinder chambers, A_1, A_2 are the piston areas, A_{rod} is the rod cross sectional area, y is the piston position, M is the mass of moving parts attached to the cylinder rod, $\boldsymbol{\sigma}_{cyl}$ is the cylinder damping coefficient, F_{load} is the load force at the actuator rod, and F_r is the cylinder friction. The right side of Eq. (3) is also implemented in the model to further validate the force signal calculation, it takes into account the dynamics of the piston and the friction force of the cylinder as well as the load applied at its rod [8] [9].

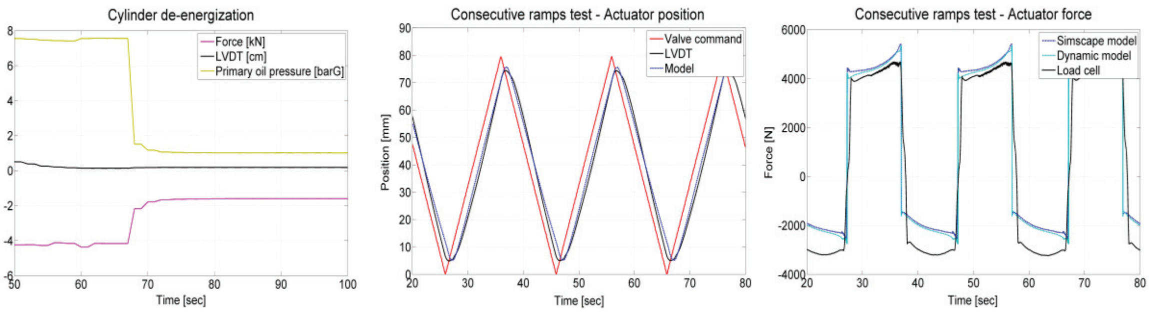
Each block in the simulation is configured according to the design parameters of a ST control valve system of a small combined cycle plant (CoGen plant) running at GE O&G - Nuovo Pignone in Florence.

4. Model validation and test results

A dedicated test campaign focusing on the actuation system and control valve assembly was accomplished at the CoGen plant. The control valve of this ST went through an upgrade of its actuation system to improve the efficiency of the whole regulation, giving the possibility of carrying out a specific comparison between legacy and new EHA system performances. Particularly, the tests performed with the former one gave detailed data suitable for both model validation and system characterization. In order to achieve this, the legacy system has been equipped with a specific test rig: a position sensor (Linear Variable Differential Transformer (LVDT)) giving the displacement of the hydraulic actuator and a load cell of load pin type measuring the actuation force required for control valve movement. Two pressure sensors on the primary and secondary oil lines were also installed to provide a direct input to the model for validation purpose, being primary oil circuit and I/H converter electronics out of the scope of the analysis. Furthermore, a dynamic data acquisition system was required with a capability of sampling experimental data at the interval of 0.5 ms (2 kHz) for fast valve movement characterization.

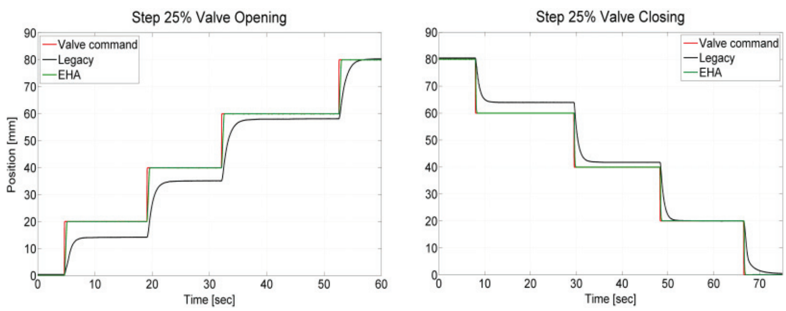
The test campaign was pursued by keeping the emergency stop valve closed so that no steam was able to reach the steam chest ahead of the shutters of the control valve, in order to avoid considering the steam force contribute and, in this way, to calibrate the mechanical system and validate the model. The system has been analyzed both in static conditions and with dynamic valve movements such as ramps and steps for the achievement of its complete characterization.

Figure 2 shows tests made with the legacy system. Figure 2.a presents the cylinder de-energization procedure performed by decreasing the primary oil pressure to atmospheric pressure and maintaining the actuator in valve closed position. This test aimed at determining the weight of the system from the trend read by the load cell, to be considered as an offset for the following measures.



(a) (b) (c)

Fig. 2. Results of the tests on the legacy system.(a) cylinder de-energization procedure, (b) actuator position; (c) force matching during consecutive ramps test



(a) (b)

Fig. 3. Comparison of the accuracy of the Legacy and EHA systems on valve opening (a) and closing (b)

Figures 2.b and 2.c represent the correspondence between simulation results and experimental data in terms of, respectively, actuator position and force. These two signals are plotted in the same time frame of a consecutive ramps test commanded from the governor as represented by the red line. In Figure 2.b the trend in blue dotted line is the one gathered from simulation and shows a good match with the measured position, indicated as LVDT, both in terms of accuracy and dynamic response. This result is fundamental for the achievement of a dynamic characterization of the system and, consequently, for a major awareness on the dynamic requirements when evaluating new actuation technologies. Force calculated with pressures from cylinder chambers is referred to as *Simscape model* whereas the one determined with actuator dynamic equation is named *Dynamic model*. These two signals are compared to the load cell data in Figure 2.c and such comparison further highlights the consistency of the model.

The comparison between the two different actuation technologies (see Figure 3) puts into evidence that EHA is much more accurate in reaching the position commanded giving consequently less uncertainty on control valve precision and, thus, on steam inlet characterization. Nevertheless, it should be taken into account that the legacy system has been working in the plant for several months and it is likely that this type of system can incur in un-calibration after long operation.

5. Conclusions

The paper presented goes through the extensive research that has been put in place on ST control valve systems, focusing both on their predictive models and on opportunities for actuation system technology upgrading. The developed study aimed at providing a solid model of the control valve system when operated without steam, that represents a strong basis for the further development of the model that will involve the steam force contribute analysis and model implementation. The capability of simulating the behavior of the control valve response when operated with steam comes along with the opportunity for performing critical ST regulation phase simulations through the integration with the governor logic and machine drums models. This will represent a digital instrument for the analysis of their interaction inside the entire control loop which can be embedded in the ST governor with the aim of performing advanced diagnostics and analytics and consequently checking regulation performances degradation.

Future work will be in line with the growing interest towards EHA technologies bringing the need of covering the entire fleet of actuation systems with their corresponding model. This achievement would both enable the analysis of the performances of this type of actuators and the study of their behavior when interfaced to the rest of the system.

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Biography

Maddalena Pondini obtained a Master degree in Energy Engineering from Politecnico di Milano and is currently working with TeCIP Institute since 2015. Her activity focuses on model based solution approaches for steam turbine optimized operability and this specific research is carried out together with GE O&G Nuovo Pignone, Florence.