Development of RT models for Model Based Control-Diagnostic and Virtual HazOp Analysis

A. Biagini [1], R. Conti [1], E. Galardi [1], L. Pugi [1], E. Quartieri [2], A. Rindi [1], S. Rossin [2]

[1] *University of Florence, via di S. Marta 3, 50139, Florence, Italy*
[2] *General Electric Nuovo Pignone, via Felice Matteucci, 50139, Florence, Italy*

Abstract-The use of simulation tools for industrial system analysis is continuously increasing in Oil & Gas applications, (such as the development of lubricating systems). In particular Virtual HazOp (acronym of Hazard and Operability) analysis is an important tool to optimize the plant in terms of diagnostics for Maintainability, Safety, Risk assessment and management. Also the use of simulation tools can drastically increase speed, efficiency and reliability in the design process of safety critical systems. Authors, in collaboration whit GE-Nuovo Pignone, have developed a library of customizable models of thermal-hydraulic components, through an innovative thermal-hydraulic library, that is an extension of the Simscape libraries in Matlab-Simulink™. Furthermore, this tool is optimized for Fixed Step solvers to make easier the simulation of complex interactions with digital logic components, controllers and the fast prototyping of Real Time code. Aim of the proposed tool is non-destructive testing for production purposes. Results of the Virtual HazOp analysis are presented, according to the simulation of the model carried out, and automatically performed through a graphical user interface. In this work, two case studies are then presented: a lubrication system of an auxiliary system of a rotating machine and a RunDown Tank applied to a rotating machine.

Keywords- Lube oil console, Virtual HazOp analysis, Safety critical system, Non destructive testing.

I. Introduction

Object of this work is the development of a multiphysics tool for the monodimensional analysis and failure simulation of thermal-hydraulic systems. In particular, the tool is developed in the Matlab-Simulink environment and has been customized for the simulation of oil lube plants with a particular attention to the application of virtual HazOp analysis (acronym of Hazard and Operability). The tool, called Virtual HazOp toolbox, is the product of the cooperation between the University of Florence (in particular the MDM Lab) and the industrial partner GE Oil & Gas Nuovo Pignone. Virtual HazOp toolbox represents an innovative trade off among different features proposed by known commercial software and the internal specifications of GE-NP procedures.

In particular, the toolbox should be easily customizable in order to integrate virtual HazOp analysis in the GE product workflow:

- *Automatic model generation*: a simulation model can be automatically generated assembling a pre-defined population of sub-models directly from GE technical database and documentations available in the P&ID (piping and instrument diagram) drafting tool PidXP™;
- *HIL Simulation (Co-Simulation with GE-NP controller)*: HIL-SIL approach for the development and the verification of plant controllers such as is a quite interesting and potentially useful approach which is currently performed using the Matlab-Simulink environment. As a consequence there is a great interest to maintain the compatibility with Mathworks™ tools which support automatic code generation for different targets.

Considering the over mentioned applications two main requisites of the tool have to be assured:

- *Optimization for Fixed Step solvers and R-T implementation*: considering the previously described use for HIL and SIL testing the tool should be used for the fast prototyping of RT code. This application involves the use of fixed step solvers to obtain a deterministic task time with pre-defined computational resources. Also Automatic generation of C-code for a real time target should be supported, considering fixed step computation and compatibility with almost all the supported target compilers;
- *Robustness*: the tool will be used to simulate virtual HazOp (component failures or off-design conditions) during the design process. These critical situations often correspond to a bad numerical conditioning of the simulation parameters. So Robustness is a mandatory specification.

One of the aims of the proposed tool is to simulate the thermal hydraulic transient of a plant, considering off-design conditions, which are often associated to pressure-temperature working ranges where the fundamental properties of the fluids such as viscosity and density could change in an appreciable way. In particular, in the Virtual HazOp toolbox the real behaviour of the fluid is modelled, considering the variability of the various coefficients as polynomial functions of fluid pressure and temperature and extrapolating the fluid properties respect to reference conditions.
The general approach followed in literature [5], [6], [10], [11] according to Bond Graph multiphysics modelling procedure for a mono-dimensional flow, is described in terms of mass conservation, momentum and enthalpy balances.

In order to reproduce the dynamical behaviour of thermal hydraulic systems, PDEs (Partial Differential Equations) should be solved. Following the approach, similar to the suggested examples in literature [12], [13], and usually adopted by commercial software like LMS Amesim™, the plant is discretized in lumped elements where the PDEs are re-written in terms of control volume balances. Therefore, the system can be described by an ODE (Ordinary Differential Equation) system, composed by a bi-directional network of connected capacitive (tanks, pipes...) and resistive components (valves, orifices...). Resistive elements describe the equation of momentum conservation. The inputs are the temperature and the pressure of the adjacent blocks and calculate the enthalpy and the mass flow. Capacitive elements are characterized by equations of continuity (conservation of mass) and energy (enthalpy balance). The inputs are the specific enthalpy, the mass flow and the heat exchanged with the external environment, and thanks to the adjacent blocks the temperature and the pressure are calculated. The models have been optimized and specifically designed according to the P&ID definitions and regulation in force ISO 14617.
In particular, to perform Virtual HazOp in each block there are also defined parameters and dynamical inputs to control the failure state of the component to partially automate the simulation of sequential or multiple failure states. These models allow an analysis of the critical points in generic plants from the reliability point of view. Indeed, in parallel to the modelling activity, the purpose is to obtain automatically a reliability scheme of generic industrial plant.

II. Automatic model generation

Automatic Model Generation from plant sketches reduce errors introduced by data transcriptions and operator misbehaviour. In order to make easier the automatic creation of the model, data consistency of data exchanged by the assembled sub-models has to be automatically assured and verified. So, the Simulink model can be automatically generated by P&Id schemes taken from GE PidXP™ configuration tool (an engineering tool/database for the definition and sketch of thermal-hydraulic systems).
Using a simple tool internally developed by GE, the user is able to automatically extract a network topology from a P&Id scheme of the thermal-hydraulic system, where each component is associated to the corresponding database of properties and technical information, and allows the automatic generation of the model using remote construction instructions. The topology of the automatically generated model is very similar to the P&Id scheme since there is 1:1 correspondence among P&Id symbols and the dynamical models. Even relative positions of components are reproduced to define an intuitive approach. It is important to notice that since the model is created in Matlab-Simulink™, further customization and modifications are still possible, considering that most of the parameters are masked and the blocks are accessible as standard masked subsystem. The workflow corresponding to Automatic Model Generation from GE-NP PidXP™ is schematized in Figure 1.

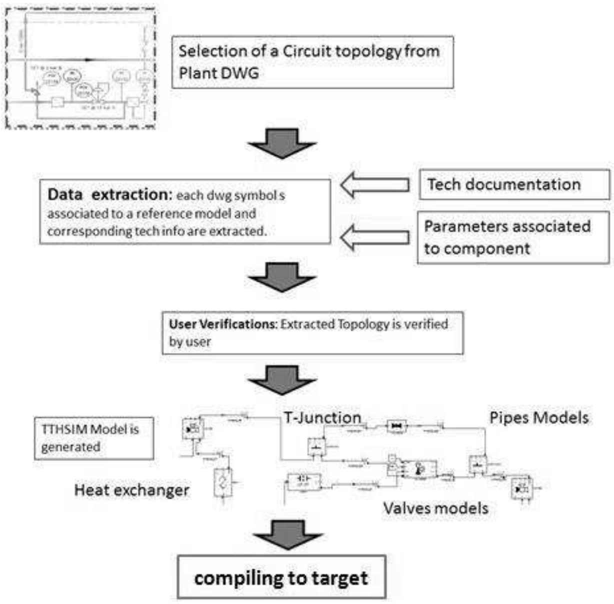

Figure1. Typical workflow from GE P&ID scheme to the corresponding Virtual HazOp toolbox

It's interesting to notice that the software is designed with a modular approach so an expert user may directly drag & drop blocks to produce its own heavily customized code for simulation.
On the other hand standard analysis can be also performed by intermediate and entry level users following an automated-guided process which drastically reduce the risk of human errors and assure a safe and repeatable way of working.

III. Virtual HazOp analysis of a lubrication system

The first case study (Figure2) is a complex unit used to lubricate hydrostatic compressor bearings. This lube oil console is characterized by two centrifugal pumps operated by two asynchronous motors. A manual valve has been inserted to simulate the failure of the pipe upstream of the Check-valves. The plant continues with a cooler stage applied in parallel with an orifice; these pipes are connected through a 3-way Temperature Control Valve, used to regulate temperature downstream the valve (controlled by the GE-NP *MARKVIe* controller). Beyond the TCV, a filtering stage, two Gas-tanks (gas preloaded accumulators) and a Pressure Control Valve is implemented. The gas tanks are used to compensate the oil flow during the transients, i.e. when the *ac* voltage is down or a failure occurs. The PCV is a self regulated pressure control valve for the regulation of the downstream pressure, with a bypass branch placed in parallel. Finally, the hydrostatic compressor bearings are modeled as an equivalent orifice (load), placed after a vertical pipe stage. Additional orifices, Check-valves and by-pass valve are added to the plant to simulate other known lumped losses or failures. The lube oil console model, implemented with the TTH library, is validated with an equivalent model developed with LMS Amesim™ (commercial software), performing different operating conditions, in which fault conditions are also considered.
The results of the Virtual HazOp analysis are presented, according to the simulation of the model carried out with the TTH library, and automatically performed through a graphical user interface (a GUI, called Virtual HazOp toolbox), developed by authors, which represents an innovative trade off among different features proposed by known commercial software and the internal specifications of GE-NP procedures. Using the simplified model described above, different failures or operating conditions can be simulated. The failures of the components are defined according with GE-Nuovo Pignone experiences and each component simulates its failure behaviour. In the Virtual HazOp toolbox, the failure list, summarized in Table 1, is automatically created defining the topology and the components. In preliminary validations, the lube oil console is modelled into the Virtual HazOp toolbox and in the commercial code, by defining the maximum case of the possible failures; the possible scenarios are increased in order to simulate availability and reliability of pressurized gas tanks. It is worth to note, since the model is created in Matlab-Simulink™, further customization and modifications are still possible, considering that most of the parameters are masked and the blocks are accessible as standard masked subsystem.

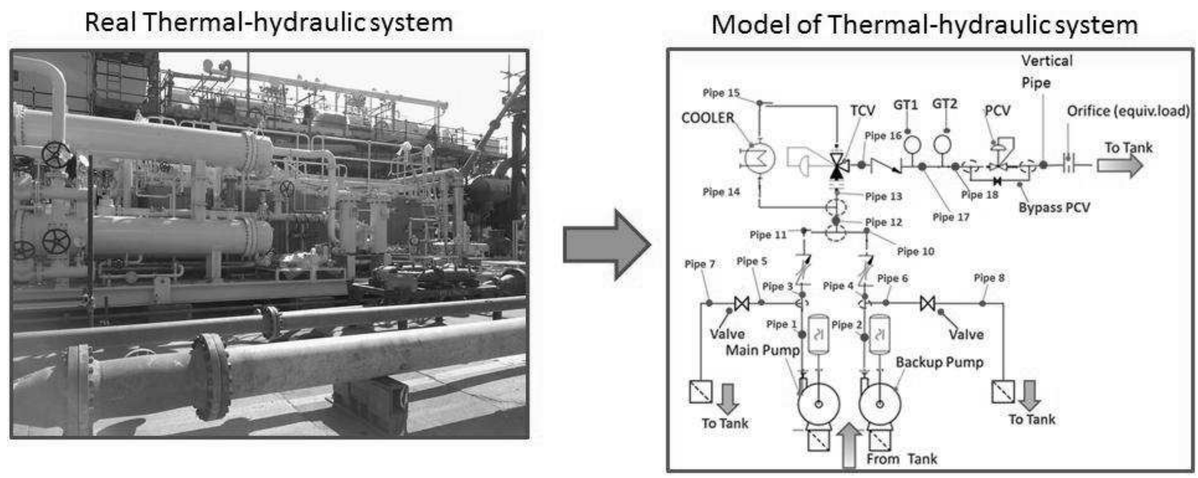

Figure2. Model of the thermal-hydraulic system

Failure	Description
Opening PCV bypass valve	The PCV bypass valve is manually open to analyse the response of the controller.
Failure PCV	The PCV is manually forced to open its inlet.
Failure hot TCV	The TCV is manually forced to close the hot inlet only.
Opening main pump bypass valve	The main pump is manually bypassed by a valve that simulates the breakage of the pipe.
Opening auxiliary pump bypass valve	The auxiliary pump is manually bypassed by a valve that simulates the breakage of the pipe.
Failure main pump	The failure consists in the breakage of the machine and thus leads to a sudden decoupling of the main pump by the electric asynchronous motor.
Failure auxiliary pump	The failure consists in the breakage of the machine and thus leads to a sudden decoupling of the auxiliary pump by the electric asynchronous motor.
Failure cooler	The failure consists in the breakage of the cooler and thus heat exchanged whit environment becomes zero.

Table 1. List of failures

Among the various failure list, in this work the authors are focused on the failure "*Opening PCV bypass valve*" in order to analyse both failure behaviour and the thermal-hydraulic stability. In Figure 3, the comparison between the temperature measured after the TCV outlet is shown: the dynamical behaviour of the TCV is nearly similar, the little differences can be associated with different control or implementation strategies in the two models. In addition, the pressure measured in collector point is shown; as can be see, the system behaviour is really similar. The pump bypass valve opening is enabled at $20\ s$, as a consequence, the pressure reaches an initial value of about $3.7\ BarA$. Then, the PCV pressure decreases in few seconds trying to follow its set-point (that is about $2.8\ BarA$), thanks to the PCV control system, which is forced to close the PCV passage section in order to reject the additional flow disturbance introduced by the opening of the bypass valve.

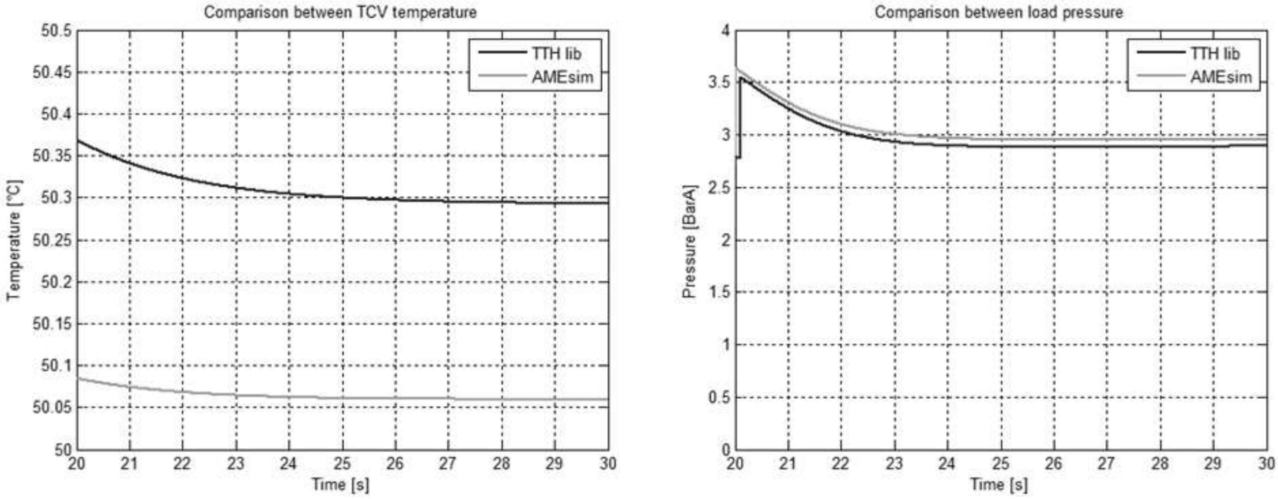

Figure3. Comparison between TCV temperatures (left) and load pressures (right) obtained whit TTH library (Matlab-Simulink™) and LMS Amesim™.

The tests performed to evaluate the physical thermal-hydraulic behaviour can be analysed through several indexes:

- *Load pressure error*: the maximum relative difference between the load pressures (E_{LP}) calculated by the two simulation software;
- *Collector pressure error*: the maximum relative error between the collector pressures (E_{CP}) ;
- *TCV temperature error*: the maximum relative error between the two simulated temperatures in outlet of the TCV (E_{TCVT}).

These indexes can be used to describe in a synthetic manner the coherency among the different tests. In Table 2, E_{LP} E_{CP} and E_{TCVT} values calculated for different failure conditions showing a good agreement between the two simulation software corresponding to maximum errors of about $1 - 1.5\%$.

Failure	$\mathbf{E_{LP}}$	$\mathbf{E_{CP}}$	$\mathbf{E_{TCVT}}$
Opening PCV bypass valve	*<1.5%*	*<1.5%*	*<0.5%*
Failure PCV	*<1.5%*	*<1.5%*	*<0.5%*
Failure hot TCV	*<1%*	*<1.5%*	*<0.5%*
Opening main pump bypass valve	*<1%*	*<1.5%*	*<0.5%*
Opening auxiliary pump bypass valve	*<1%*	*<1.5%*	*<0.5%*
Failure main pump	*<1%*	*<1.5%*	*<0.5%*
Failure auxiliary pump	*<1%*	*<1.5%*	*<0.5%*
Failure cooler	*<1%*	*<1.5%*	*<0.5%*

Table 2. Error evaluations

IV. RunDown Tank analysis

The second analyzed case is referred to the RunDown Tank (Figure 4), that is a customizable thermal-hydraulic tank, modelled in the TTH library, used for oil accumulation and release oil in the lubrication system, and validated thanks to experimental results. The input stage is represented by a Group Valve, realized by the parallel of a main manual valve, an adjustment 3 *mm* orifice and a check-valve, which allows the transit of inlet or outlet oil flow. The output stage is realized by an overflow pipe, consisting of a short horizontal conduct which then converges directly, by a tube with vertical orientation, into the tank of the lube oil console. This pipe is used for the exceeding oil release, if the oil height within the reservoir exceeds the level at which the hole, formed in the wall of the tank, is located. Note that the oil flow release from the overflow pipe increases until it reaches equilibrium with the incoming/input flow of the tank. The behaviour of this tank is studied, in order to verify if particular operating conditions should cause an undesired siphon effect on the overflow pipe able to produce an abnormal draining of the tank. This effect occurs when there is no return air flow, against the oil, in the overflow pipe between vertical RunDown Tank and tank main unit. In normal operating conditions, a two-phase flow [1] which is thus generated, as a result of an initial transient in the highest part of the pipe, is constituted by an annular oil flow, that runs downwards, adhering to the pipe wall, and in parallel by a column of air ascending. The problem corresponding to siphon effect, subsists in the case in which the oil flow rate is high enough to fully occlude the conduit. In this way the air reflux is no longer permitted and the effect is triggered, which causes a rapid (and unwanted) emptying of the reservoir which, possibly, due to the depression generated as in the free volume of the oil inside the RunDown Tank (RDT), causes damage to the component. Also, this effect must be avoided, because a minimum volume of oil must remain in the tank, in order to stop the machine safely, when *ac* voltage is off or a lube oil console component failure occurs. Simulated tests are aimed at checking that the dimensionless Froude Number [1], [2] in equation (1), according to international standard rules, is less than a certain threshold (*0.3*) which assure that the potentially dangerous siphon effect is avoided.

$$Fr = \frac{v}{\sqrt{Dg}} = \frac{4Q_v}{\pi D^2 \sqrt{Dg}} \tag{1}$$

where:

- v represents the fluid speed in the pipe;
- D is the inner pipe diameter;
- g is the gravity acceleration;
- Q_v defines the fluid volumetric flow.

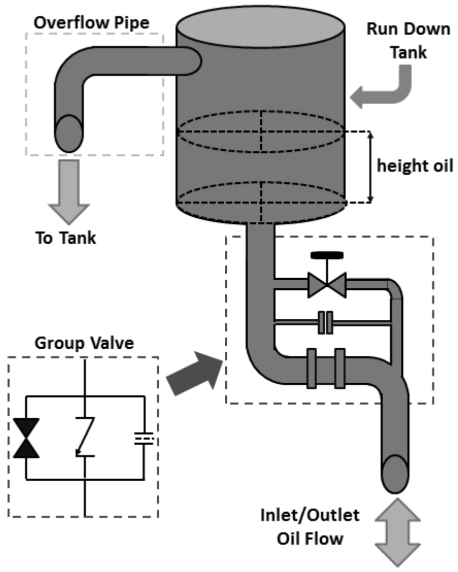

Figure 4. GE-Nuovo Pignone customizable RunDown Tank.

In particular the following failure scenario is simulated: both supply valves are kept open, thus simulating a fault condition of the system, that can't switch between a valve and the other, in terms of flow regulation. The purpose of these tests is to check the Froude Number varying the C_q value on the main manual valve. Tests are carried out considering the following parameters, expressed in Table 3.

Parameter	Value	Unit of measure
Overflow Pipe diameter	4	Inches
RDT section	3.74	m^2
Pressure inlet flow	2.7	$BarA$
Overflow pipe height	1.75	m
RDT-lubrication system height difference	5.25	m
Temperature	50	$°C$

Table 3. RunDown Tank tests parameters

In Figure 5, the Froude Number behaviour depending on the flow coefficient is shown: the values reported in Figure 5 show that a C_q greater than about 5.5 Froude Number should exceed the critical value of 0.3, producing a potential risk of triggering a potentially dangerous siphon effect.

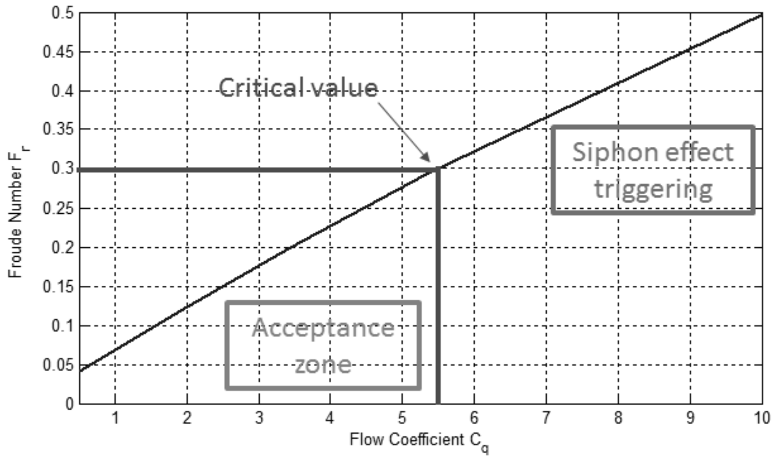

Figure 5. Froude Number behaviour depending on the main valve Flow Coefficient.

V. Conclusions

During this work, the authors have implemented in Matlab-Simulink™ a thermal hydraulic toolbox, the Virtual HazOp toolbox, in which the failure analysis can be completely automatized and can be also evaluated during the plant design. Moreover, inside the Virtual HazOp toolbox, it is implemented a procedure to automatically convert the P&Id scheme of GE-Nuovo Pignone into the proper dynamical model.

The thermal-hydraulic behaviour of the toolbox has been cross-validated by comparing simulation results with the corresponding ones calculated by a commercial software (LMS Amesim™). Comparison have been performed considering several plants and failure scenarios. In particular, the coherency among different failure tests in a complex unit, used to lubricate hydrostatic compressor bearings is analysed. Then, the correct behaviour of a RunDown Tank is focused, since it represents a particular safety critical component. Therefore, an analysis of the critical points in generic plants from reliability point of view is allowed.

As regard the future developments, it is planned an experimental campaign on different lube oil console in which the characterization of the thermal-hydraulic behaviour of the GE hydrodynamic journal and thrust bearings will be focused. In particular in the actual implementation bearings are modelled as equivalent orifices with an assigned flow-pressure relationship which is calculated from GE-NP and manufacturer data which are mainly referred to steady-state-nominal working conditions. Moreover, in parallel to the modelling activity, the main purpose is to automatically obtain a reliability scheme of generic industrial plant. This objective could be reached considering a larger population of test results, and a greater number of different components.

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