Techniques Used to Design Reliable Control Systems.
A Case Study: Electrical Geothermal Plant from the University of Oradea, Romania

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ABSTRACT

The demands placed upon control systems in respect to reliability continue to increase as these systems become integrated into a wide variety of safety-critical applications. For these categories of applications, it is essential to be able to guarantee that all critical processing is accomplished accurately and on time Adan and Magalhaes and Ramamritham (1998).

Consequently, the increasing complexity of the real-time control systems demands for new techniques that can be applied during all the development phases of the system. This paper presents a set of steps, concepts and criteria that can be used for critical real time process control design; consequently, an increased reliability can be achieved Irwin (1996).

An example of how these concepts were used in order to design a highly reliable real-time control system is presented using a case study: the electrical geothermal plant from the University of Oradea. The paper outlines the fact that the proposed techniques address one of the most important issues regarding real-time control systems design: reliability. It also provides a structured, disciplined and highly visible development Puchol and Mok (1998).

1. INTRODUCTION

Generally, real-time control systems are critical and expensive to build. Moreover, they are costly to run due to the hardware costs and manpower requirements Zmaranda and Cretu (2000). Therefore, it is highly desirable to test as much on the system's design as possible prior to its actual implementation. Moreover, the usual approach should be dynamic testing, which implies testing during all the development phases Bequette (1998).

Among several testing phases, a very important issue is design testing. For critical systems, the reliability testing is crucial during design phases: and this could be done using reliability/availability diagrams, which are different from the system's functional schemes. It is important to achieve an overall view about system's reliability and availability from the early stages of the design Svrcek and Mahoney and Young (2000).

2. STEPS IN RELIABILITY ASSESMENT

The following steps should be followed in the reliability assessment process:

- divide the system into tree basic levels: system level, subsystem/module level and component level Goble (1992). For reliability analysis purpose all this three level of a system should be considered. Proper cognizance is routed in the lowest level of the system

- reliability model construction based on system's physical model, it's operation and failure modes. In the reliability

model components may be connected differently from the physical model Johnson (1993)

- reliability/availability calculation, evaluation and analyzing using the rules of probability. For non-repairable system reliability will be considered; for repairable systems, availability is used in turn Kercecioglu (1991).

- finalize the assessment process by proposing some improved reliability schemes using redundant components Leitch (1995)

3. ORADEA GEOTHERMAL POWER PLANT RELIABILITY ASSESSMENT

3.1. SYSTEM OVERVIEW

The geothermal power plant is a component of the cascaded geothermal energy utilization system, and is used to convert the energy of the geothermal water into electrical energy using CO_2 as working fluid. The elements of the power plant are the following: vaporizers (heat exchangers used to vaporize the CO_2), a reciprocating engine connected with the electric generator, a make-up and expansion CO_2 tank, condensers (heat exchangers used to condense the CO_2) and a CO_2 pump.

As mentioned above the geothermal power plant uses CO_2 as a working fluid. The thermodynamic cycle presented in Figure 1 shows the different evolution stages of the working fluid and it has to ensure the heat transfer between CO_2 and the geothermal water or cold water.
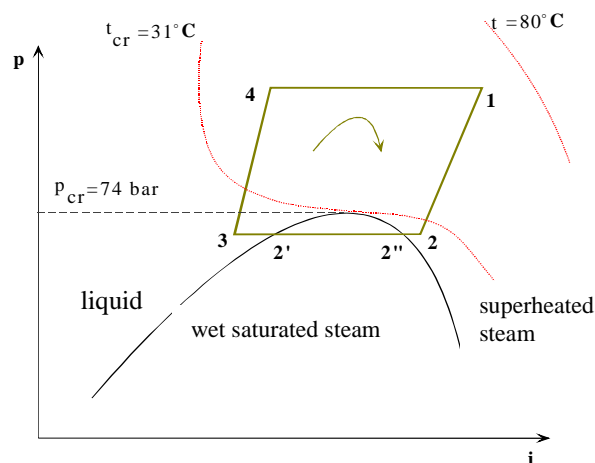

Figure 1. Thermodynamic cycle of the working fluid

Gabor and Zmaranda

The evolution from state 1 to 2 represents the expansion of the CO_2 inside the engine generating mechanical work that is transformed into electrical energy; 2 to 3 transition represents the evolution of CO_2 inside condensers where the heated CO_2 is used to heat the cold water and has three distinct sub phases (see Figure 1); 3 to 4 state transition is the compression of CO_2 into the CO_2 liquid pump; the 4 to 1 transition represents the CO_2 evolution inside the vaporizers where the gas is heated through the heat exchanger using geothermal water.

3.2. CONTROL SYSTEM STRUCTURE
The control system scheme for the thermodynamic cycle of the geothermal power plant is shown in Figure 2.

The control system has to maintain constant the CO_2 pressure and temperature in all the important states of the thermodynamical cycle Smith and Corripio (1997).

As it can be seen from Figure 1 it ie enough to maintain constant the temperature and pressure in states 1 and 3

because the 3 to 4 transition is an adiabatic compression and the transition from 1-2 is an adiabatic expansion. In order to control the thermodynamical cycle it's enogh to control the CO_2 temperature t_1 after vaporisation in the heat exchangers (at the engine admision) and t_3 the CO_2 temperature at the after condensation into the heat exchangers.

We have also to control h the CO_2 liquid level from the tank in order to insure an accurate CO_2 pump functioning (Figure 2).

Table 1 contains the main control loops from the geothermal power plant together with the controlled parameter tendency and the expected reaction of the system Gabor and Gavrilescu (2002).

Figure 3 shows the logical scheme used in order to control the $t3$ temperature Phillips and Harbor (1996)
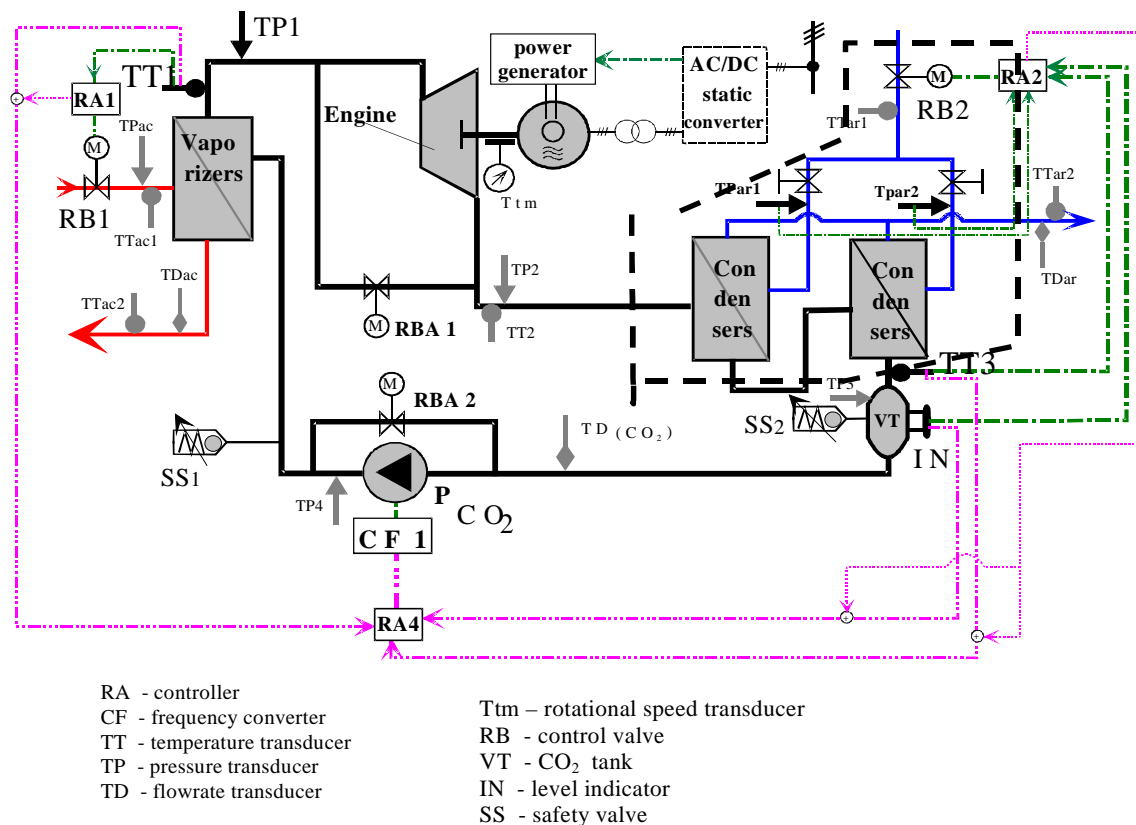

RA - controller
CF - frequency converter
TT - temperature transducer
TP - pressure transducer
TD - flowrate transducer

Ttm – rotational speed transducer
RB - control valve
VT - CO_2 tank
IN - level indicator
SS - safety valve

Figure 2: Control system block scheme

Table 1. Control loops in the power plant

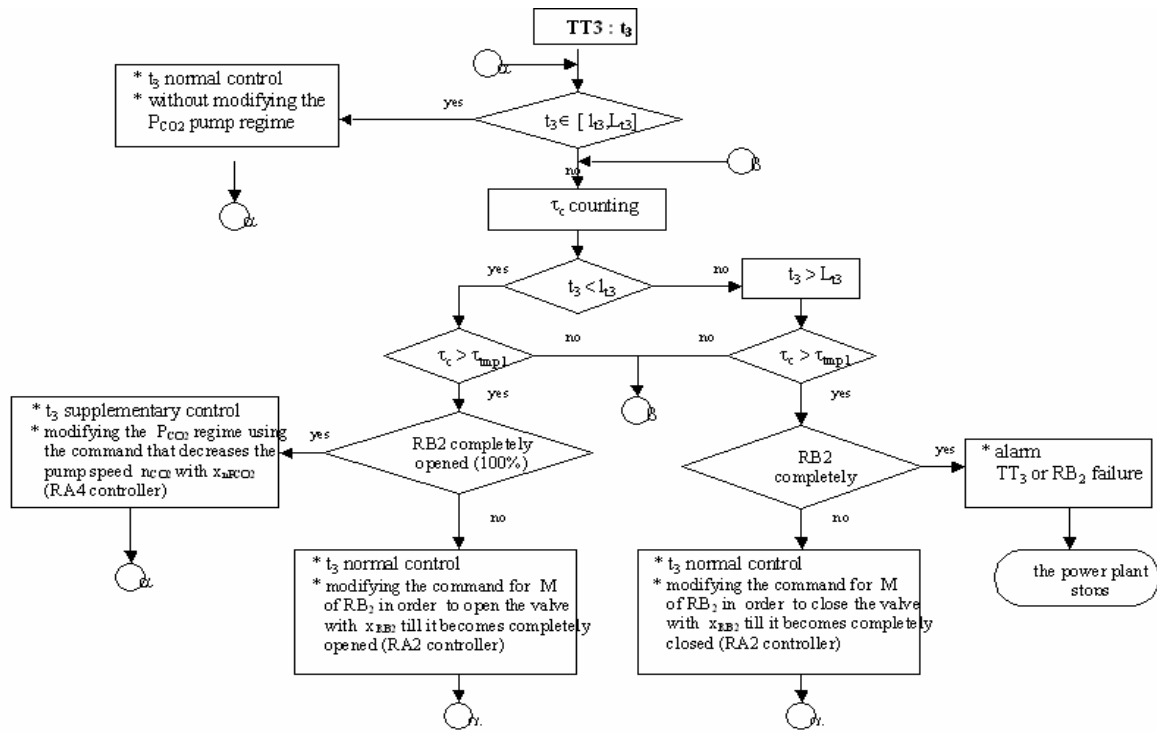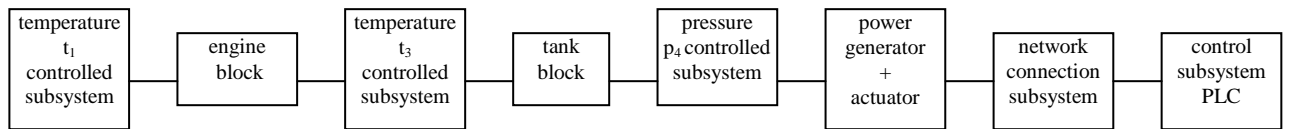| Controlled parameter /loop	Parameter tendency	Expected reaction
t1/ TT1,RA1,RB1, vaporizers	Increases	- geothermal water flow rate decreases
		- geothermal water flow rate increases
	Decreases	- CO_2 pump speed decreases
t3/ TT3,RA2,RB2, condensers		- cold water flow rate increases
	Increases	- CO_2 pump speed decreases
	Decreases	- cold water flow rate decreases
h/ IN,RA2,RB2,condensers	Decreases	- cold water flow rate increases
		- CO_2 pump speed decreases

2

Figure 3: The logical scheme used to control the *t3* temperature

Figure 4 : Reliability scheme for the geothermal power plant
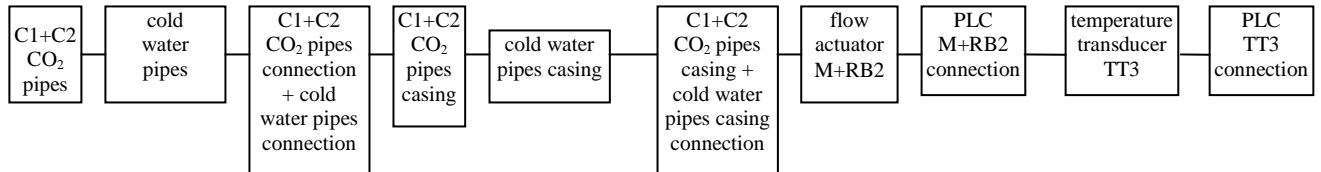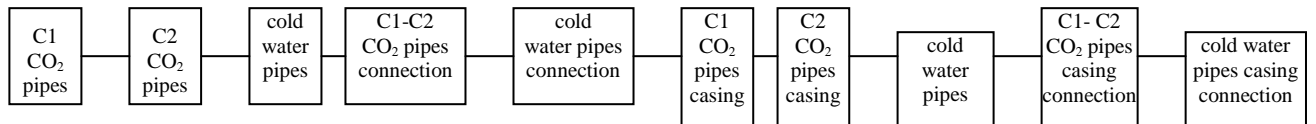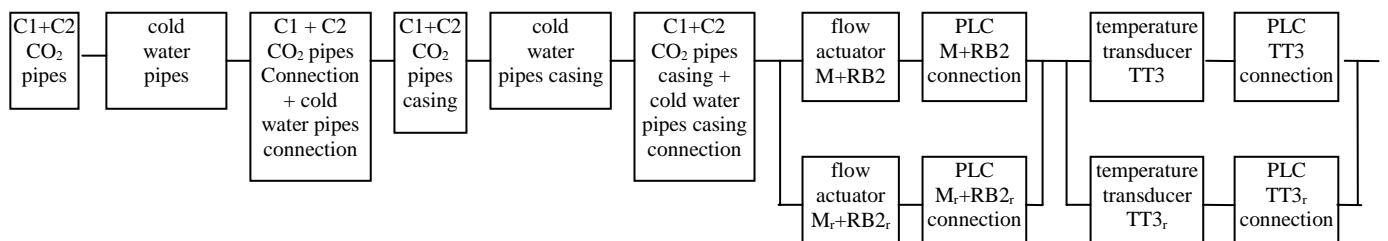

Figure 5. Realiability scheme for the temperature t_3 controlled subsystem

Figure 6. Reliability scheme for condensers

Figure 7. Reliability scheme for the temperature t_3 controlled subsystem using redundancy

3.3 RELIABILITY AND AVAILABILITY ASSESSMENT

3.3.1.Reliability model construction

In order to be able to study the control system's behavior presented in Figure 2 from reliability or availability point of view first we have to implement realistic and credible reliability/availability schemes Bentley (1999).

Figure 4 shows at systems and block level the reliability scheme for the thermodynamic cycle of the geothermal power plant (first level considered). The subsystems of the controlled loops implemented are controlled using a PLC (the control subsystem).

The second phase considers the reliability/availability scheme (shown in Figure 4) detailed at subsystem level. Figure 5 shows the detailed reliability/availability scheme for temperature t_3 controlled subsystem. This subsystem is delimited in Figure 2 using a dotted black line. The data gathered for the other subsystem from Figure 2 are not presented into details in this paper.

If we take a look to the structure from Figure 5 it can be seen that the main critical points are represented by the flow actuator (motor M + RB2) and the temperature transducer TT3. At component level, the reliability scheme is shown in Figure 6, which cosiders all its elements.

3.3.2. Reliability/availability analysis

In order to obtain a higher value for the reliability/availability for the temperature t_1 controlled subsystem we proposed the redundant scheme from Figure 7. We obtained this scheme including in the scheme shown in Figure 4 extra entities (we doubled theflow actuator and the temperature transducer) in the main crical places mentioned before Gabor G., and Popescu (2003).
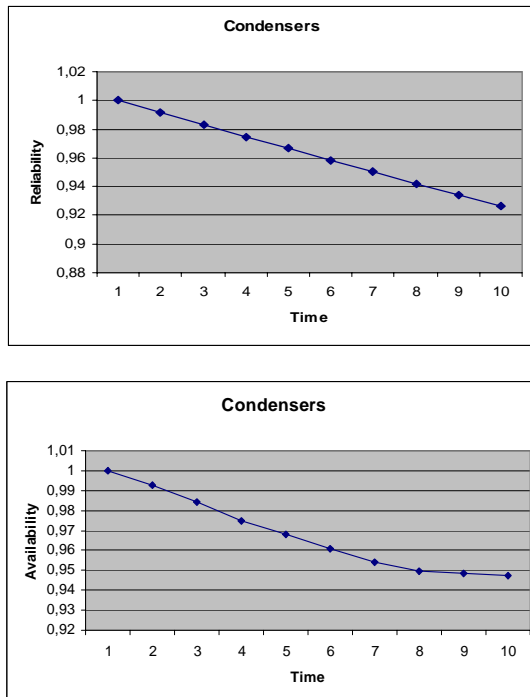

Figure 8: Reliability/availability for condensers

Based on the scheme from Figure 6, a comparison between choosing nonrepairable/repairable components should be

done. Figure 8 shows that better results could be obtained by using repairable elements (availability is greater than reliability)

In order to compare the reliability or availability of the schemes presented in Figure 5 and Figure 7 we consider the individual failure and repair rates shown in Table 2.

Table 2: Individual failure and repair rates

ELEMENTS OF t_3 TEMPERATURE CONTROLLED SUBSYSTEM	INDIVIDUAL RATES	
	λ [week^{-1}]	μ[week^{-1}]
C1+C2 CO2 pipes	0.000228	0.0415
Cold water pipes	0.000225	0.0416
C1+C2 CO2 pipes – cold water pipes connection	0.000215	0.005
C1+C2 CO2 pipes casing	0.000182	0.0415
Cold water pipes casing	0.00018	0.0416
C1+C2 CO2 pipes casing - cold water pipes casing connection	0.000175	0.005
RB2	0.000154	0.05
Motor of RB2	0.000057	0.416
PLC - motor of RB2 connection	0.00021	0.005
TT3	0.00012	0.05
PLC – TT3 connection	0.000156	0.005

Based on individual failure and repair rates presented in Table 2, in Table 3 it is estimated the availability for two distinct cases: for the reliability scheme from Figure 5 (without redundancy) and for the reliability scheme from Figure 7 (with redundancy).

Table 3: Comparative availability values

ELEMENTS OF t_3 TEMPERATURE CONTROLLED SUBSYSTEM	AVAILABILITY	
	A (with redundancy)	A' (without redundancy)
C1+C2 CO2 pipes	A1 = 0.99453	A1' = 0.99453
Cold water pipes	A2 = 0.99222	A2' = 0.99222
C1+C2 CO2 pipes – cold water pipes connection	A3 = 0.95877	A3' = 0.95877
C1+C2 CO2 pipes casing	A4 = 0.99563	A4' = 0.99563
Cold water pipes casing	A5 = 0.99570	A5' = 0.99570
C1+C2 CO2 pipes casing - cold water pipes casing connection	A6 = 0.96619	A6' = 0.96619
RB2 (*)		A7'=0.9862522
Motor of RB2 (*)		A8'=0.9859224
PLC - motor of RB2 connection (*)	A7-9=0.998756	A9'=0.9845352
TT3 (**)		A10'=0.9875664
PLC – TT3 connection (**)	A10-11=0.997413	A11'=0.9875243

Generally, in Table 3 A' represents the availability of the scheme without redundancy, while A represents the availability of the scheme with redundancy. Elements denoted with (*) in Table 3 correspond to the first redundant

group while those denoted (**) correspond to the second redundant group.

Because only for RB2 and TT3 and their connections we used redundancy (Figure 7), the values for A and A' are different only for A7-A7' to A11-A11'. The availability of the structure presented in Figure 7 was obtained using the following relations:

$$A = A1 \cdot A2 \cdot \ldots \cdot A7\text{-}9 \cdot A10\text{-}11 \qquad (1)$$

and for the sheme from Figure 5:

$$A' = A1' \cdot A2' \cdot \ldots A9' \cdot A10' \cdot A11' \qquad (2)$$

According to Table 3 the availability values are different only for the part of the scheme that use redundancy. Based on data values from Table 3 and relations (1) and (2) in Figure 9 a comparison between A (availability without redundancy) and A' (availability with redundancy) is presented.
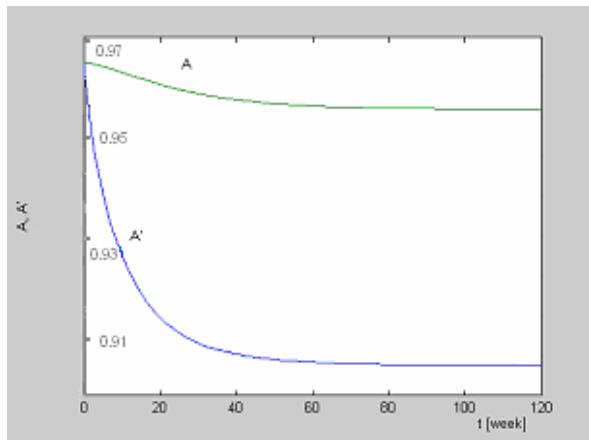

Figure 9: Availability with and without redundancy

It can be observed that availability increases when using redundant components. Redundant components can be used at any level (component, sub-system and system) thus improving global system availability.

The above-presented calculations were done at sub-system level (t3 control loop sub-system) but can be extrapolated at any level, including the system level.

CONCLUSIONS

The paper reveals the results obtained considering two distinct case studies for availability calculations for the t3 controlled sub-system component of the geothermal power plant control system.

During the calculation individual failure and repair rates were taken into account. The analyze was carried out based on availability schemes for t3 controlled sub-system with and without redundant components.

The results obtained conclude that redundant component usage significantly improves the availability of the sub-system.

Extending this analyze to the whole system (to all its sub-systems) provides a mode to increase the global availability by using redundant components in the main critical points of the system.

For several safety critical control systems the above analysis provide a very useful method to estimate system reliability/availability properties and reveals its critical points where redundancy may be used.

For these categories of control systems, it is essential to be able to guarantee their availability and safety functioning in all conditions.

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