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Reliability Improving Techniques Using Redundant Structures for the Geothermal Power Plant from the University of Oradea, Romania

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ABSTRACT

The demands on control systems in respect to reliability continue to increase as these systems are integrated into a wide variety of safety-critical applications. In critical applications, it is important to be able to evaluate if the data gathered from all transducers of the control system are valid.

This implies that the control system must be implemented using redundant structures, which represents alternatives if a malfunctioning element is detected. This paper presents a method used to design and implement such a control system based on redundant structures that will be used for the geothermal power plant at the University of Oradea.

The control algorithm was extended with parts that determine if some elements are functioning correctly and, eventually, switch to a redundant element, if necessary. The proposed redundant structures are simulated using Matlab/Simulink and analyzed using different scenarios. Finally, a solution of the resulting control system structure with redundant transducers is implemented using an Allan Bradley PLC.

1. INTRODUCTION

PLC related applications are more complex as far as more components are involved. If some error occurs, diagnosis can take some time, but a logical procedure will shorten the time needed to locate the fault. The probability of failure of different parts of typical PLC systems shows that 95% of PLC systems are external faults and occur on plant items such as: sensors, actuators, transducers, limit switchers, and others Curtis (2007).

The possibility of determining the validity of the data gathered from all transducers of the control system assures a way of short time fault detection. Consequently, a fault-tolerant control system must be implemented using redundant structures, representing an alternative for malfunctioning element detection Dhillon (2007). This paper presents a method used to design and implement a control system based on redundant structures considering double and triple redundancy for the temperature transducers.

The control algorithm was extended with parts that determine whether some components/transducers are functioning correctly and if they fail the control system switches to the existing redundant component/transducer Jurgen (2003). A case study for the geothermal power plant at the University of Oradea was developed. The double and triple redundant structures considered were simulated using MathLab/Simulink and analyzed using different scenarios. Finally, a possible implementation of resulting control system structure is done using a programmable logical controller PLC) www3 (2009).

The paper outlines the fact that the proposed method addresses one of the most important issues regarding control systems design its reliability and it also provides a structured, disciplined and highly visible development.

2. CONTROL SYSTEM STRUCTURE

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 Gabor G. and Zmaranda (2005): 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.

The control system has to maintain constant the CO_2 pressure and temperature in all the important states of the thermodynamic cycle. In order to control the thermodynamic cycle it's enough to control the CO_2 temperature t_1 after vaporisation in the heat exchangers (at the engine admission) and t_3 , the CO_2 temperature at the after condensation into the heat exchangers. We also have to control h the CO_2 liquid level from the tank, in order to ensure an accurate CO_2 pump functioning (see Figure 1).

The whole control system shown in Figure 1 was simulated using MatLab/Simulink. The simulation file obtained for the vaporizers zone is shown in Figure 2. The calculation of temperature t_1 from the process is implemented in the vaporizers block noted "vaporizatoare" (see Figure 2). This block contains the differential equations which successively determine the geothermal water flow rate which flows through the valve and the vaporizers(Q_{ac}), the output temperature of CO_2 after the vaporizers entering into the engine (t_1) and the geothermal output temperature from the vaporizers (t_{eac}).

The control is made based on the output of the summation block, which realizes the difference between the value that results from the simulated process and the reference value Franklin and Powel (2002). Based on this difference, the output signal for opening the RB1 valve is given. The temperature t_1 is measured using the temperature transducer TT1, which is implemented in the simulation program using the block „*trad_TT1*".

The simulation file obtained for the condensers zone is shown in Figure 3. The calculation of temperature t_3 from the process is realized in the condensers block.. The control is made based on the output value of the summation block, which determines the difference between the value that results from the simulated process and the reference value. Based on this difference, the output signal for opening the RB2 valve is given. The temperature t_3 is measured using the temperature transducer TT3, implemented in the simulation program using the block „*trad_TT3*".

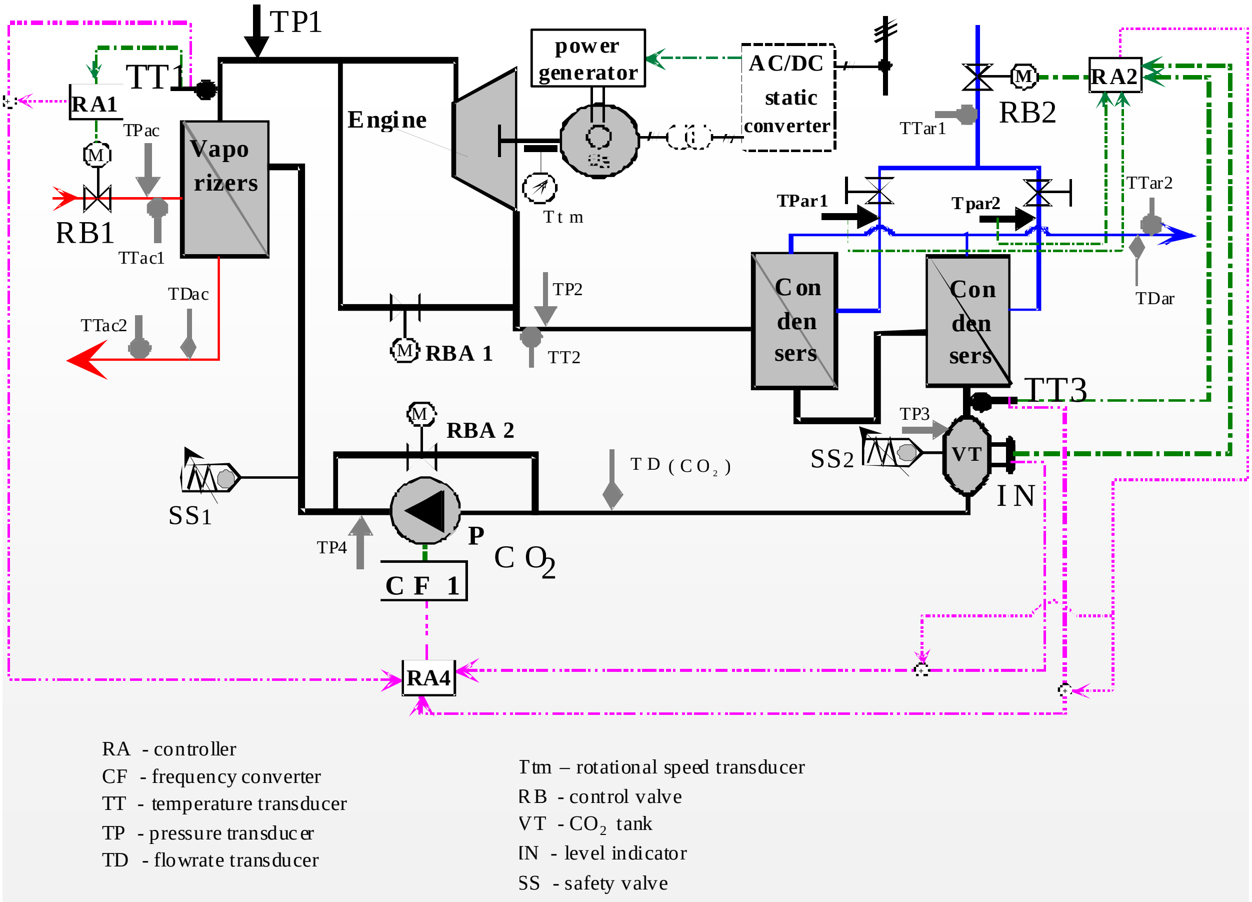

Figure 1. The control system structure

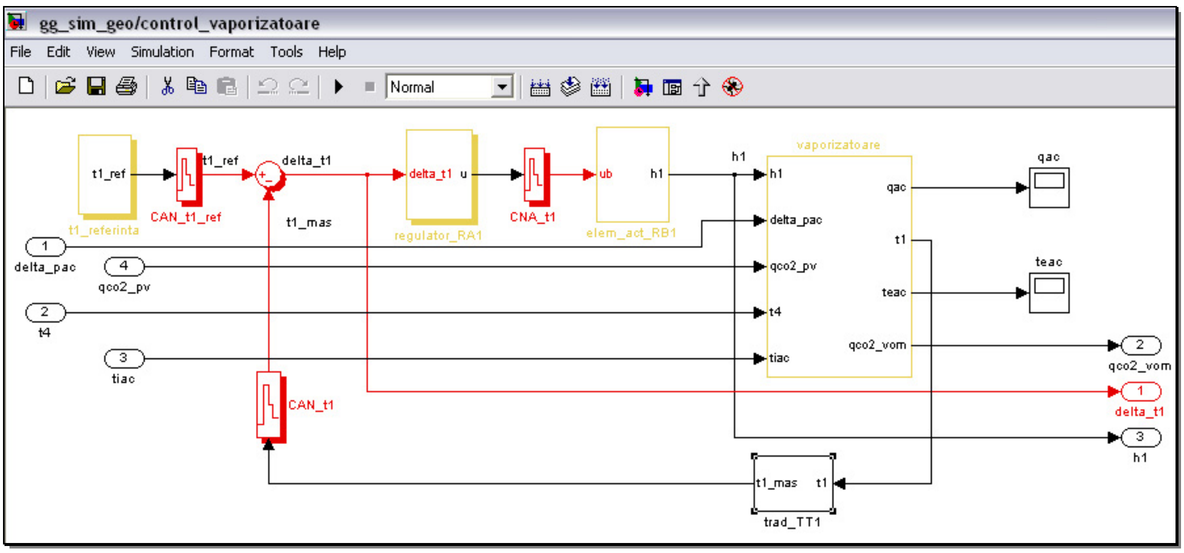

Figure 2. Simulation for vaporizers zone (t_1)

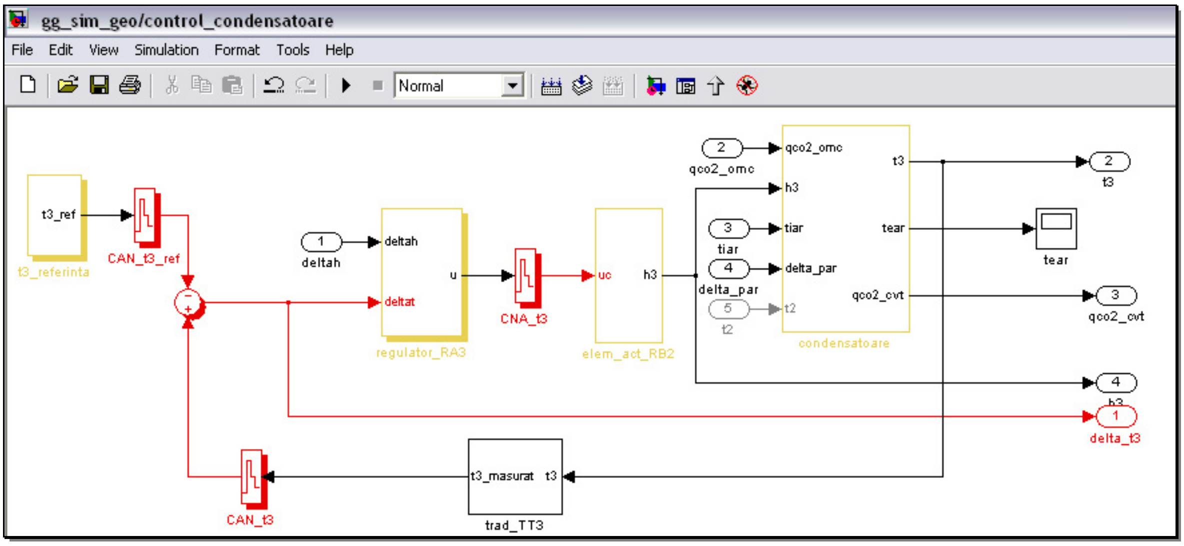

Figure 3. Simulation for condensers zone (t_3)

In order to improve the reliability of the control system by assuring correct measurement of temperatures t_1, and t_3, redundant structures are considered. Next chapter analyzes the possibility of using double redundancy for TT1 temperature transducer and triple redundancy for TT3 transducer.

3. REDUNDANT CONTROL STRUCTURES

3.1 Double redundancy for t_1 temperature measurement

For the correct measurement of the temperature t_1, a redundant structure is used. Consequently, in the simulation program, the simple structure for temperature t_1 measurement named „trad_TT1" in Figure 2 was replaced with a redundant structure containing two temperature transducers TT1 and TT1r respectively. Assuming that both transducers TT1 and TT1r are functioning, in order to determine which of them gives the correct masurement, the scheme from Figure 4 is used.

In the scheme from Figure 4 t_{1_1} is the temperature from the TT1 transducer, t_{1_r1} is the temperature from the TT1r transducer (redundant transducer), t_{eac} is the temperature from the Teac transducer, t_1 is the real system temperature, t_{1ref} is the reference temperature, t_{1_mas} the temperature value that is used as a control variable for the RB1 valve, RA1 is the controller used to control the t_1 temperature and RB1 the controlled valve. In order to evaluate if the system is functioning correctly, and to determine which transducer measures correctly the temperature t_1, a correlation with another temperature from the system is done. This temperature is denoted by t_{eac} and is measured by the Teac transducer.

To evaluate the correct functioning for both TT1 and TT1r transducers, the value indicated by the Teac transducer is considered. Based on the simulation we used different scenario and after analyzing the data gathered, we obtained a set of rules. These rules were used to identify which transducer is functioning correctly and to obtain the correct value that will be used for RA1 controller.

RULE 1_1 *– if the reserve transducer output (TT1r) is variable and the output of the transducer Teac is constant, that implies that TT1 transducer functions correctly and the reserve transducer is failed; consequently, the system should use the already connected transducer TT1.*

For implementation of RULE 1_1 the following variables were used: *sumTT1r* – the sum of the variations of the TT1r transducer output; *deltasumTT1r* – represents the threshold value for *sumTT1r; sumteac* – the sum of the variation of the temperature measured by Teac transducer; *deltateac* – threshold value for *sumteac.*

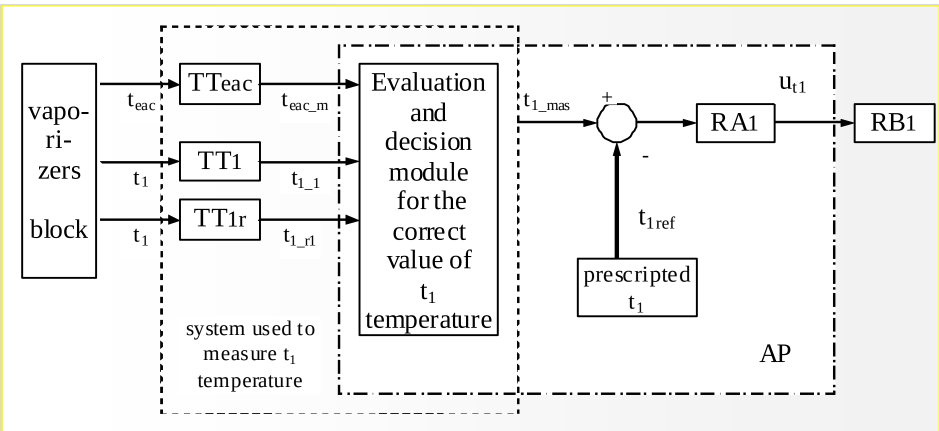

Figure 4. Block scheme for correct value evaluation of the t_1 temperature obtained using a redundant scheme for measurement (TT1 and TT1r transducers)

If the absolute value for *sumTT1r* is greater than the upper limit *deltasumTT1r*, and *sumteac* is not greater than *deltateac*, then a signal indicating that TT1r is failed is generated to the operator periodically:

|sumTT1r| > deltasumTT1r and |sumteac| < deltateac
$\Rightarrow$ TT1r failed, continuing using TT1

RULE 1_2 *– if the reserve transducer output (TT1r) is variable and the output of Teac transducer varies in the same way, then the functioning TT1 transducer is failed and the reserve transducer if functioning correctly; consequently, the system should change and use the reserve transducer TT1r.*

In order to implement RULE 1_2, the following variables were used: *sumTT1r* – the sum of the variations of the TT1r transducer output; *deltasumTT1r* – represents the threshold value for *sumTT1r; sumteac* – the sum of the variation of the temperature measured by Teac transducer; *deltateac* – threshold value for *sumteac.*

If *sumTT1r* and *sumteac* have the same sign, and each of them is above the uuper limit *deltasumTT1r* and *deltasumteac* respectively, than a signal indicating that TT1 failed is sent to the operator. Also, the controller output connects to TT1r:

(sumTT1r · sumteac >0) and |sumTT1r| > deltasumTT1r
and |sumteac| > deltasumteac
$\Rightarrow$ TT1 failed, system connected to TT1r

To determine the sum of the variations of temperature values measured by TT1r and Teac transducers, a number of NE (NE=5) measured values were considered for calculating the average variations.

3.1 Triple redundancy for t_3 temperature measurement

We considered a triple redundancy for the temperature transducer that measures temperature t_3. So the simple structure for temperature t_3 measurement named „trad_TT3" in Figure 3 was replaced with a redundant structure containing the following temperature transducers TT3, TT31r, TT32r.

These three transducers are working continuously and we considered that a transducer fails if its measurement overflows a threshold value (the mean value of the values indicated by all these three transducers). After a transducer fails, we consider the mean value obtained from the transducers that are still working. The first rule determined was the following:

RULE 3_0 *– If the value measured by a transducer overflows the mean value of the three values measured by the transducers considered as threshold value thna this transducer failed and it will be eliminated; the temperature t_3 used for controol it will be the mean value of the two values given by the two functional transducer.*

The case considered for 1 out of three transducers fails can be reduced to a similar case of double redundancy For the considered case of double redundancy we need a third value, considered as a trusted one. This strategy for redundant systems presumes the tracking of the mean value variation (the sum of the variation of the mean values) in nominal regime. The mean value variation increasing over a certain threshold value is considered as failure for the transducer.

The scheme from Figure 5 presents the values we have to consider for the evaluation of the correct operating transducer (TT3, TT3r1, TT3r2) in order to determine and use a correct value for t3 temperature. The condensers block supplies real temperature t3 to the transducers TT3, TT3r1 and TT3r2.

In Figure 5, t_{3_1} represents the temperature measured by the transducer TT3, t_{3_r1} the temperature measured by the spear/ redundant transducer TT3r1, t_{3_r2} the temperature measured by the spear/ redundant transducer TT3r2, t_{tear_m} the temperature measured by the transducer Tear (used as additional value) and t_{3_mas} the output of the redundant measuring system for temperature t_3, temperature value that is used as a control variable for the valve RB2.

Studying the data gathered from different scenarios, we extracted the rules corresponding to the evaluation of the transducer that operates correctly and we retained the correct value for t3, value used to control the loop using the RA3 controller.

RULE 3_1 *– If the TT3b transducer output is variable and the output of the transducer Tear is constant that implies that TT3b transducer failed and the transducer TT3a is still working.*

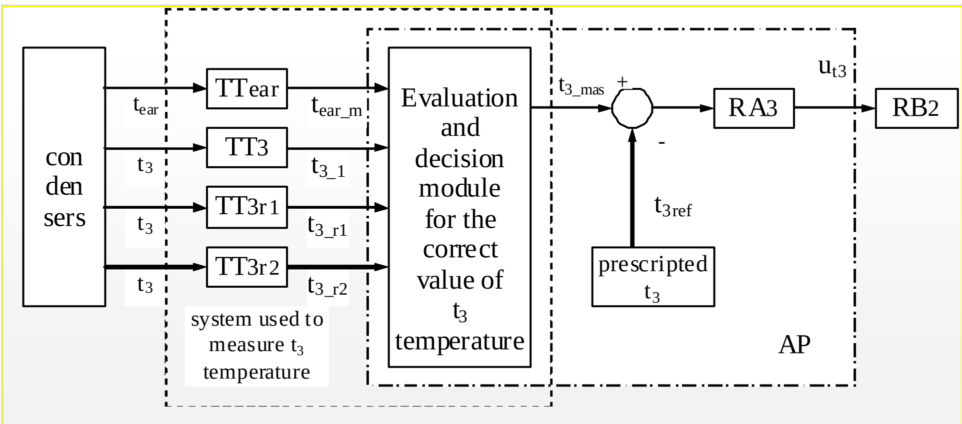

Figure 5. Block scheme of the system used to measure temperature t_3

In order to implement RULE 3_1 the following variables were used: *sumTT3b* – the sum of the variations of the TT3b transducer output; *delta_t3* – the threshold value for *sumTT3b;* *sumtear* – the sum of variations for the temperature indicated by Tear; *delta_tear* – threshold value for *sumtea.*

If the absolute value for *sumTT3b* is greater than the threshold value *delta_t3*, and *sumtear* is lower than *delta_tear*, then a signal indicating that TT3b failed is generated to the operator periodically:

|sumTT3b| > delta_t3 and |sumtear| < delta_tear
⇒ TT3b failed and TT3a is still working

RULE 3_2 *– if the TT3b transducer output is variable and the output of TTear transducer varies in the same way, then TT3a transducer failed and TT3b transducer is still working.*

In order to implement RULE 3_2, the following notation were used: *sumTT3b* – the sum of the variations of the TT3b transducer output; *delta_t3* – the threshold value for *sumTT3b;* *sumtear* – the sum of variations for the temperature indicated by Tear; *delta_tear* – threshold value for *sumtear.*

If *sumTT3b* and *sumtear* have the same sign, and each of them is above the threshold value *delta_t3* and *delta_tear* respectively, than a signal indicating that TT3a failed is sent to the operator periodically.

IF (sumTT3b · sumtear >0) and |sumTT3b| > delta_t3
and |sumtear| > delta_tear
⇒ TT3a failed, and TT3b still working

The rules presented above are applied for each two of the three transducers remained in function, even if in above rules the transducers was generic denoted TT3a and TT3b. Based on the manner in which these transducers were denoted in Figure 6, the possible cases are as follows: (TT3, TT3r1), (TT3r1, TT3r2), (TT3, TT3r2). The difference between the case of double redundancy presented for vaporizers is the fact that in this case both transducers are working. In both redundancy cases considered in this paper, the spare transducers were chosen from different manufacturers, in order to minimize similar transducer failures. The block scheme used to determine the real value for the temperature t3 measured with three redundant transducers is shown in Figure 6.

4. RESULTS OBTAINED THROUGH SIMULATION

In order to study the behaviour of the identification algorithm for the double redundancy scheme that has to be implemented on the PLC we used a simulation model developed using the Simulink scheme Tewari (2002) from Figure 6.

The scheme from Figure 6 models the identification algorithm used to identify the transducer that fails from the redundant scheme used to measure the temperature t_1 and the commutation reaction and uses a file (Matlab function) that communicates with the Simulink model. Simulation was carried out using different scenarios.

One of these scenarios considers that the functional transducer *Trad_t1* (TT1) fails and the redundant transducer remains functional, and the control system switch on the redundant transducer *Trad_t1r* (TT1r). We considered that when the failure occurred the system was in steady-state.

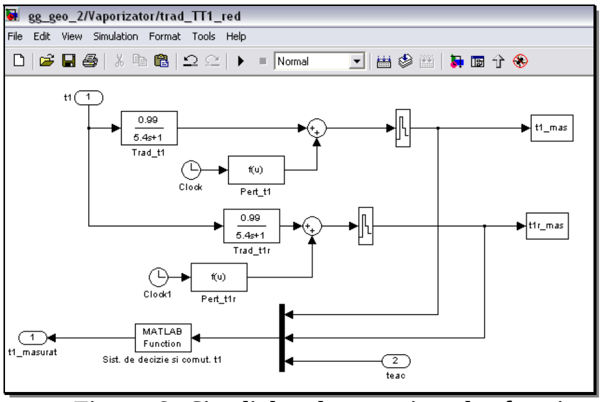

Figure 6. Simulink scheme using the function „Decision and commutation system for t_1"

The results obtained are shown in Fig. 7, and as expected, illustrate that the system is not sensitive to the temperature transducer failure and to the switching process. The failure shows up at 900 s when a negative skip of 2 degrees appears for TT1. The measurement system recover itself during 7.5 seconds and practically remains not sensitive to this failure (the oscillations between 60.5^{0}C – 60.65^{0}C are not relevant).

We also had to study the behaviour of the identification algorithm proposed for the triple redundancy scheme that has to be implemented on the PLC. For this aim we used a simulation model developed using the Simulink scheme from Figure 8.

The scheme from Figure 8 models the identification algorithm used to identify the transducer/transducers that fail from the redundant scheme used to measure the temperature t_3 and the commutation reaction it uses a Matlab function that communicates with the Simulink model www1 (2009). Simulation was carried on based on different scenarios. One of the considered scenarios corresponds to the case when the transducer Trad_t3 (TT3) fails and the other two transducers are still working. When the TT3 transducer fails the system is in steady-state. The results obtained are shown in Figure 9.

The obtained result is as expected: it detects the failed transducer and consider as value for t_3*_masurat* the average of values obtained from functional transducers: TT3r2, TT3r1.

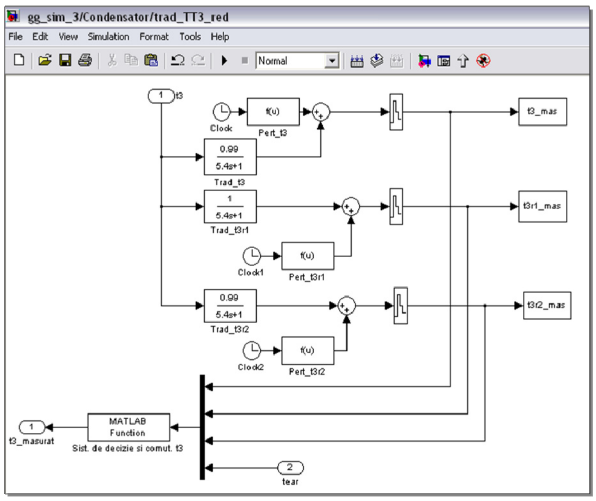

Figure 8. Simulink scheme using the function „Decision and commutation system for t_3"

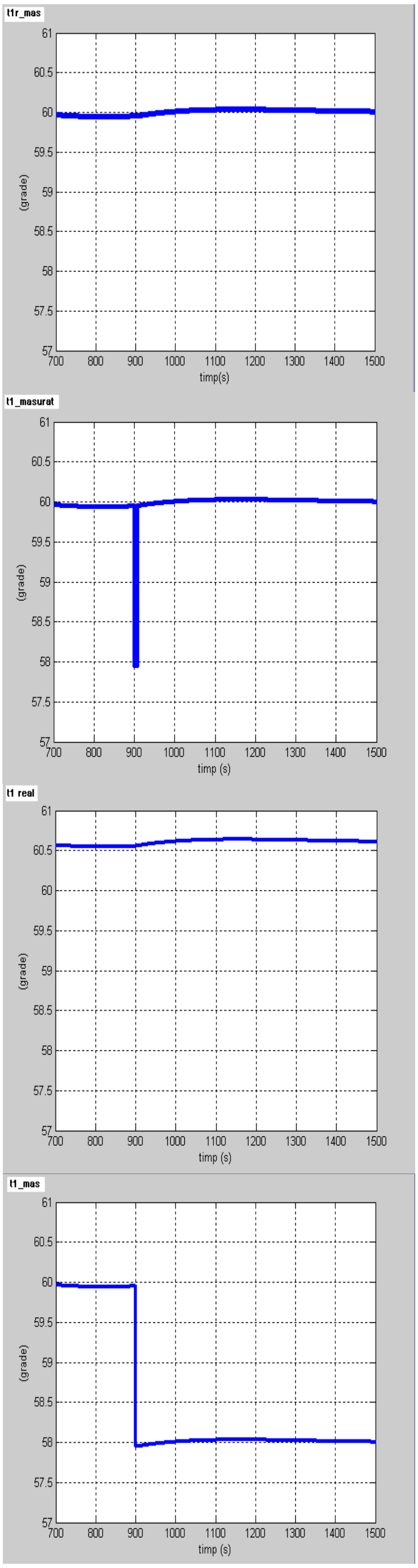

Figure 7. Values of the temperature measured by the transducer from the loop *t1_mas* (a), by redundant transducer *t1r_mas* (b), the value used by the t1 control loop, *t1_masurat* (c) and the controlled temperature t_1 , *t1 real* (d) for the scenario „TT1 failed, TT1r working/functional".

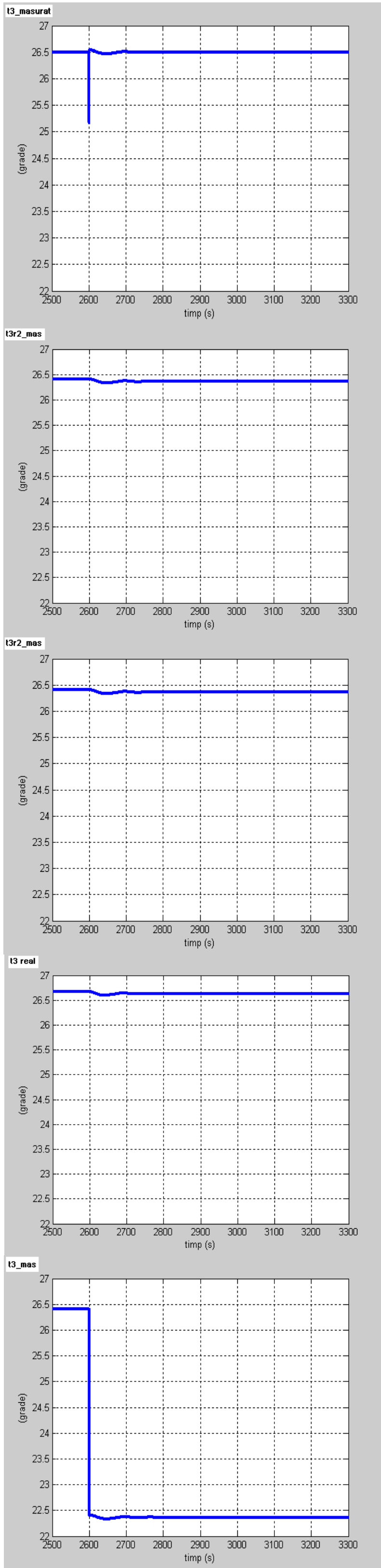

Figure 9. Values of temperatures measured by *t3_mas transducer* (a) , *t3r1_mas transducer* (b), *t3r2_mas* transducer (c), *t3_masurat transducer* (d), *t3 real* (e) for the considered scenario „TT3 failed, TT3r1 and TT3r2 still functional" Failure appears after 2600 seconds. The measurement system recover itself during 1 second and practically remains not sensitive to this failure (the oscillations between 26.65^0C – 26.45^0C are not relevant).

5. PLC IMPLEMENTATION OF REDUNDANT STRUCTURES

For implementation of the control system for the geothermal power plant, we added new modules on the existing program that includes also algorithms for TT1 and TT3 redundancy structures (Figure 10):

File #31 Initialisation of power plant conditions
File #32 Controllers in power plant (RA1,RA3,RA4)
File #33 Alarms from power plant + RAav1
File #34 Stop the power plant
File #35 Algorithm for TT1 redundancy
File #36 Algorithm for TT3 redundancy
File #37 Restarting the power plant after power-fault

Figure 10. Geothermal power plant modules

The scheme from Figure 4 illustrates the method used to evaluate the correct transducer that should be used for t_1 temperature measurement, based on RULE 1_1 and RULE 1_2. The scheme assumes that the transducers are not repairable Parr (2003).

Implementation of the method described in Figure 4 was made using an Allen Bradley Programmable Logic Controller www2 (2009) and its special programming environment APS (Advanced Programming Software) and is presented in Figure 11.

The implemented algorithm should comply with the following requirements: the algorithm allows to be activated using a special command (for example, through a button from the system user interface; however, the system must be able to function also without algorithm activation); the algorithm has to monitor the outputs from both transducers that measure the output temperature of CO_2 from the vaporizers: measured by TT1 and by TT1r but the value from Teac transducer is also needed; for each monitored value, the algorithm has to calculate the average value of NE consecutive values; NE is chosen depending on the scan cycle of the programmable controller www3 (2009) and has a default value (default NE=5 for a scan cycle of 20ms), but this value could be changed by the user; the algorithm should be able to set the reference/upper values for the TT1r (deltasumTT1r, gdeltasumTT1r) and Teac (deltaTeac, gdeltasumTeac) transducers; the average values calculated for the monitoring values will be used for activating the RULE 1_1 and RULE 1_2.

The algorithm will implement RULE 1_1 based on the following relation:

IF |sumTT1r| > deltasumTT1r AND
|sumteac| < deltateac ⇒ signals "TT1r failed"

Also, the algorithm will implement RULE 1_2 based on the following relation:

IF (sumTT1r, sumteac have the same sign) AND |sumTT1r| > gdeltasumTT1r
AND |sumteac| > gdeltasumteac

⇒ signals "TT1 failed" and changes to TT1r

We used the same method to implement the module for the triple redundancy considered for the temperature transducer TT3 based on the method described in Figure 5. The logical scheme used to implement de evaluation method on the PLC for the triple redundancy in shown in Figure 12 and corresponds to rung file # 36 from Figure 10.

CONCLUSIONS

In this paper it is developed a method for implementing redundant control system structures. The method proposed a model that considers double redundancy for the temperature transducer (TT1) and triple redundancy for the temperature transducer (TT3) based on the idea that 95% of PLC systems faults are linked with external items faults such as transducers, actuators and others external elements.

The proposed method for double redundancy is based on two rules that forms the background for detecting the valid transducer and one algorithm developed for correct value evaluation based on data gathered from redundant transducers scheme. For triple redundancy the method uses similar rules that are reduced to double redundancy ones when one of the three working transducers fails.

The algorithms developed for implemented double and triple redundancy methods were implemented using APS programming language, on an Allen-Bradley SLC-5/03 controller, and were tested using relevant scenarios. The method presented in this paper could be further extended to other parts of the existing control system were redundancy can be easily implemented.

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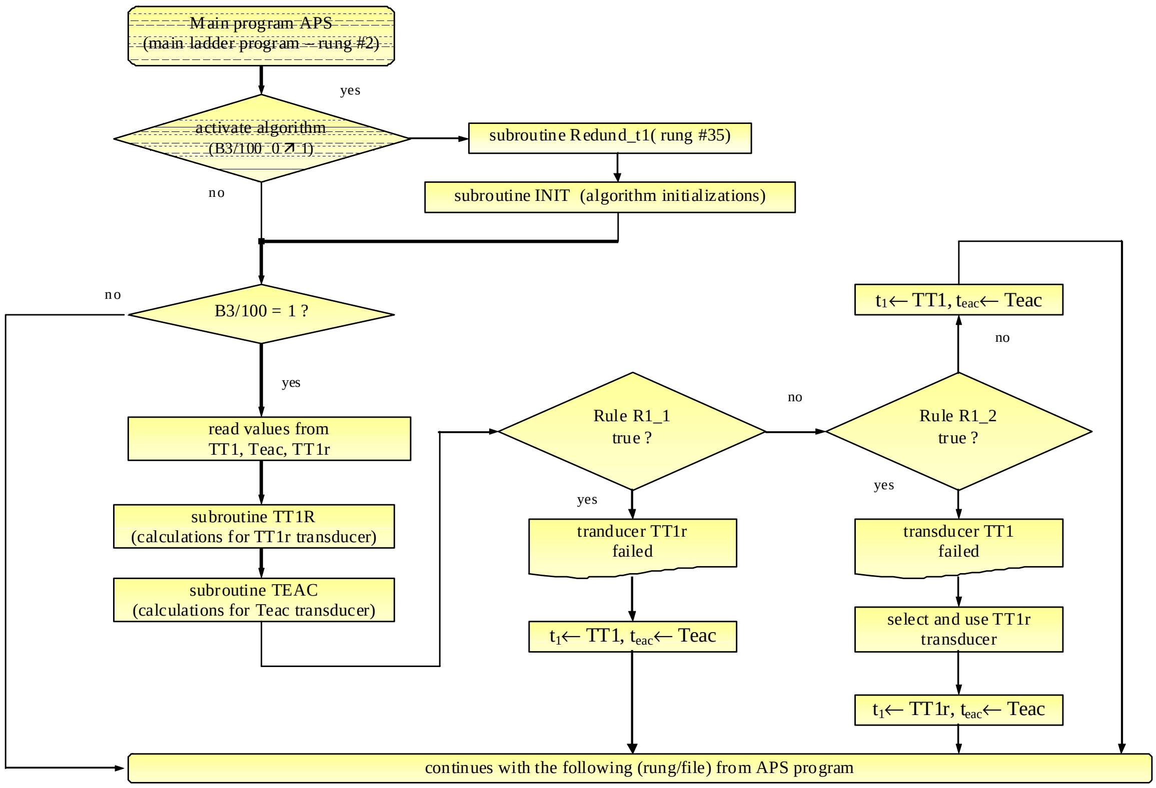

Figure 11. Logical scheme used to implement de evaluation method for double redundancy

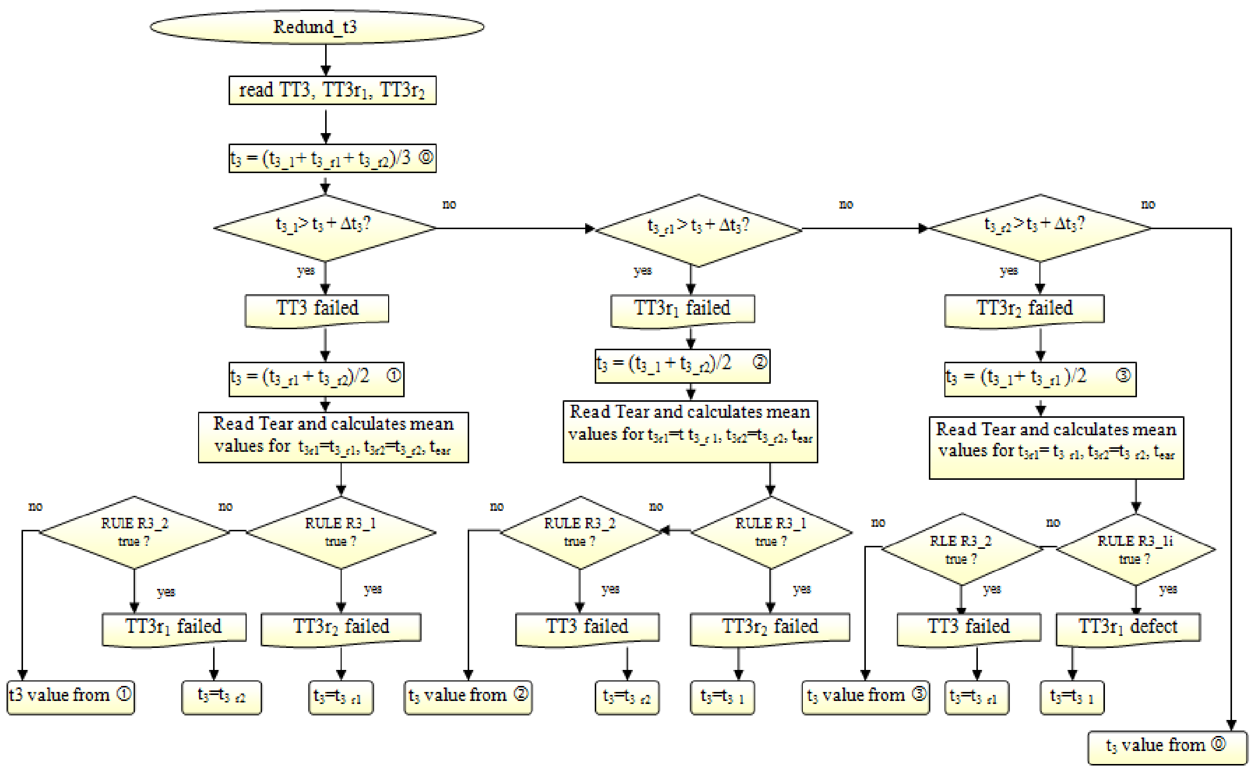

Figure 12. Logical scheme used to implement de evaluation method for triple redundancy