Contribution of Electronic Circuit Simulation to Maintain and Exploit Perpetuated I&C Systems in Nuclear Power Plants

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Abstract: As part of the extension of the life expectancy of its nuclear power plants, Electricité de France adopts a strategy of refurbishment of Instrument and Control systems, or decides to extend their lifespan them. We describe a practical experimentation showing the contribution of modelling and simulation at the electronic component level of a discrete analog system used on EDF's 900MW Nuclear Power Plant fleet. The interest of a low level model is the capability of sensitivity analysis tools to see the influence of different parameters on the overall behaviour of a function. When replacing faulty modules in operation, this approach can also be used to ensure that the new module is fully operational by comparing voltages and currents measured on the electronic circuit with the results supplied by the model.

Keyword: electronic circuit simulation, sensitivity analysis

1 Introduction

As part of the extension of the life expectancy of its nuclear power plants, Electricité de France (EDF) adopts a strategy of refurbishment of the Instrument and Control systems, or decides to perpetuate them. This latter approach is chosen mainly for systems important to safety. For the perpetuated systems, some of which are 40 years old, we raise the question of giving modern tools to the operators and engineers to facilitate their operation and maintenance.

We describe a practical experimentation showing the contribution of modelling and simulation at the electronic component level of a discrete analog system used on safety protection functions and control loops of EDF's 900MW Nuclear Power Plant (NPP) fleet. This system is based on Bailey 9020 modules, designed with discrete electronics components like resistor, operational amplifier. This technology is sensitive to its environment (temperature, humidity) and to the drift of the characteristics of electronic components (accuracy of calibration, aging). As safety related system, the ability to perform all required safety functions are demonstrated by using periodic tests during operation[1].

We have developed a SPICE (Simulation Program with Integrated Circuit Emphasis) model[2], at the electronic component level, of various modules used in a Reactor shutdown function. We were able to simulate the behavior of this function on a transient of operation and reproduce the reaction times of the real system with the Cadence OrCAD tool [3]. The interest in utilizing a low level model is to use the capabilities of sensitivity analysis tools to see the influence of different parameters on the overall behavior of a function. When replacing faulty modules in operation, this approach can also be used to ensure that the new module is fully operational by comparing voltages and currents measured on the electronic circuit with the results supplied by the SPICE model.

In the first part, we present the main characteristics of the technology used to design safety functions and control loops of EDF's 900MW NPP fleet and we also introduce the case study. In the second part, we present the development of the SPICE model, its results when used in the different modules, and the lessons learned. In the last part, we present an overview of analyses results and the perspectives of use to EDF.

2 The Bailey 9020 system

The control system Bailey is an analogue control system, developed in the late 60s. It is used in the 900 MWe and 1300 MWe units of the French nuclear fleet. It provides analogue and control functions. For the 900MWe NPP, which was commissioned in the early 1970s, it also implements the reactor protection functions (electromechanical relays implement the logic part).

2.1 The technology

The 9020 Control Bailey system is made of electronics modules. Each module implements an elementary function (multiplication, square root, threshold, PI regulator, adder, function generator ...) and uses discrete electronic components (resistance, capacitor, potentiometer, operational amplifier, diode, LSI integrated circuit …). And also uses logical components in TTL technology, mainly for generating internal power sources. The control or protection functions are designed by linking different modules. Each module is functionally adapted by manually setting potentiometers on an electric measuring bench. The exchanged signals are between 0 and 5V. Adapter modules are used to transform the 4-20 mA current loops of the instrumentation into electric tension.

2.2 Periodic tests

For safety related function, the system is designed to be periodically tested in operation. The system implements several reactor protection chains: Each chain monitors plant physical quantities on the nuclear part, and when safety thresholds are exceeded a binary order (partial reactor trip) is sent (by switching a threshold relay at the end of the chain) to the relay-based voting logics of the protection system. Fig.1 gives an example of a protection chain.

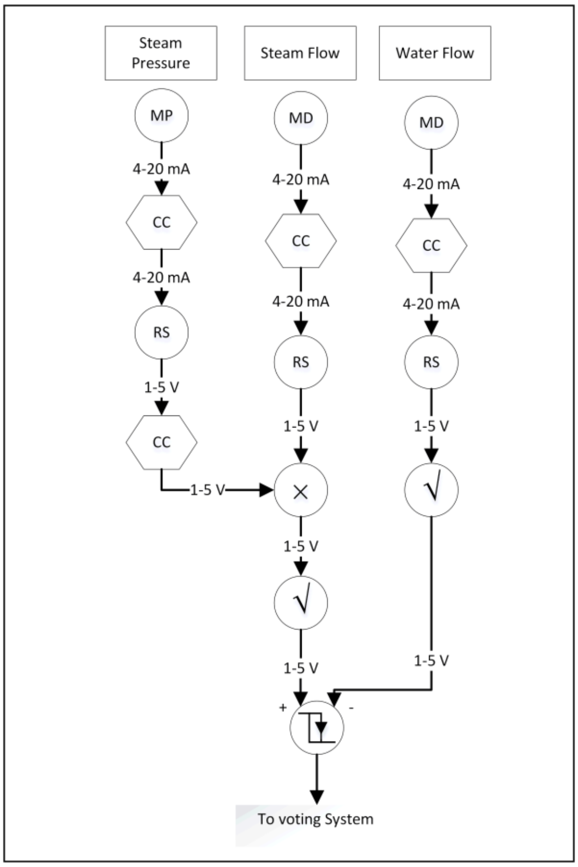

Fig.1 Protection chain example

This chain monitors 3 plant physical quantities (pressure and flow sensors via a 4-20mA current loop). Each quantity follows a processing, each defined by a specific module of the Bailey 9020 control system. Modules marked “CC” are used for periodic tests. They are detailed below. As most 9020 modules works in voltage, the "RS" modules are used to convert the voltage to current. The other modules are functional and will be detailed later.

For the periodic tests, a specific tool was developed. This tool is connected to the "CC" modules and injects electrical signals instead and the output signals are disconnected from process. At the chain output, the tool monitors the switching time of the threshold relay, as well as the voltage at its terminals when it switches. The injected ramps at the chain inputs are the electrical translation of physical ramps representative of the actual evolution of the parameters during the accidental transients where the tested chain have to react. In particular, they have variation rates comparable to transients requiring protective action. This makes it possible to test the dynamic modules in similar operating areas (the intrinsic errors of the dynamic modules depend on the change rate of the input signal). The correct behavior of the chain is validated by the following two criteria:

- The first criterion applies to the switching time of the threshold relay triggering the protection action. It allows to detect any general drift of the chain.
- The second criterion applies to the value of the switching voltage which must conform to the instrument setpoint. It ensures that there is no compensation between a drift in the chain upstream of the threshold relay and an incorrect setting of the relay leading to compliance with the first criterion.

The switching voltage of the relay must also be in a defined interval. A real chain integrates drifts and uncertainties (intrinsic errors in the modules, uncertainties related to the settings, influence of temperature, power supply voltage, sampling uncertainties, etc.). The purpose of the periodic test is to ensure that the response of the chain remains within a permissible range around the theoretical values.

Today, the calculation of the uncertainty intervals is obtained from functional models of the modules intervening in the chain, and different source of errors in the global chain (from process to the actuators). One of the aim of this study is to evaluate if an electronic component level model can be used to reduce the uncertainty margins for periodic testing.

2.3 The case study

The case of study chosen is given in Fig.1. This protection chain monitors two flows and a pressure. It uses two types of calculation modules: square root extractor and multiplier-divider. At the end of the chain, a threshold relay module allows to change the output state when the two input signals are different (with hysteresis). This chain makes it possible to initiate a partial reactor trip when the difference between the feed water flow rate and the steam flow rate of the steam generator is too high.

During the periodic test, the accidental transient corresponds to a rupture of steam generator supply piping. The flow rate decreases from 100% to 0% in a few seconds, during which time the pressure and the steam flow rate remain more or less constant. Depending on the plant, the physical values change. For our case study, the expected values are:

- The reactor trip order must be issued in 29.104s
- The voltage at the relay terminal must be 1.26V.

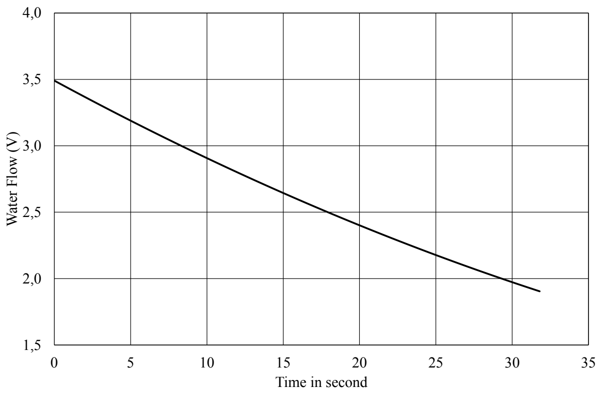

Fig.2 Water flow during accidental transient

For this first study we have modeled the square root and multiplier-divider modules. The threshold relay module has not been modeled, we have merely compared the input voltages.

3 Developing electronic models

To model and simulate the protection chains, we used Cadence's OrCAD Capture and PSpice tool. The choice of this tool is motivated by the fact that it has a large library of components and the Spice models are well suited to simulate analog electronic circuits.

We have modeled the various modules from the electronic diagrams and the component parts list of the supplier. All modules have a manual explaining how to set them. Depending on the module type, the setting is either generic, as for the square root extractor, or specific to the protection chain where the module is installed, as for the multiplier-divider module. For these latter modules, we relied on the operating documents used on the plant to adjust the modules.

3.1 Square Root extractor

This module receives an electrical signal between 1 and 5 V as input and outputs an analog signal from + 1V to + 5V proportional to the square root of the input signal. Functionally, 1V represents the value 0 and 5V the value 1.

The module has five segment generators, based on operational amplifiers and diodes. They are locked by a specific bias voltage. Depending on the change in input signal, segment generators are unlocked as soon as the input voltage cancels the bias voltage. The output is the sum of the unlocked generators. Thus the calculation of the square root is approximated by a six-segment function.

The module is powered by 28V DC. In order to power the various operational amplifiers, the module generates other voltages, sometimes using digital components, such as NAND gates, in an astable multivibrator assembly.

Since the time constants between the generation of the internal power supplies and the purely analog part of the module are different, we have approximated the internal voltages by Spice DC voltage sources. The impact of temperature on internal voltages can be studied by a specific dedicated model.

Almost all of the module components existed in the PSpice component library except for two discontinued operational amplifiers. We have replaced them with their equivalent: LM 212H and LM 312H from National Instrument, respectively by LM 101A and LM 301A from TI.

The module must be calibrated for use. The calibration procedure is described in the supplier's operating instructions. In practice, the procedure consists in injecting a precise voltage on particular points of the board and in adjusting, by setting potentiometers (seven for this module), a voltage on particular measuring points. In a Power Plant it is a delicate process, because the accuracy of the settings is at mV and some potentiometers are very sensitive. On the module's numerical model the sensitivity analysis facilitates this calibration step. Indeed, by performing a sensitivity analysis on the potentiometer to be adjusted, the correct setting value is easily found. FIG. 3 shows the sensitivity analysis on the values of a potentiometer, which had to be adjusted to the measuring point voltage tilt.

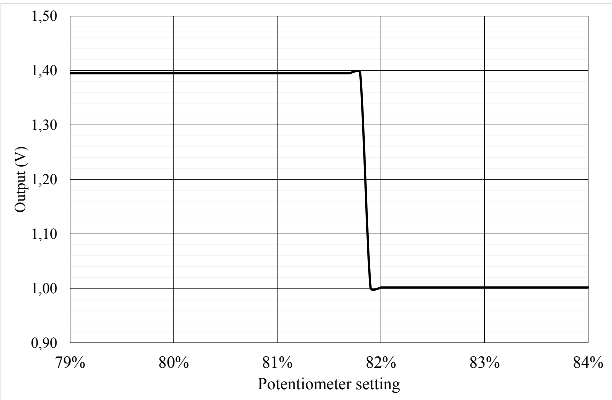

Fig.3 Parameter sweep analysis

3.2 Multiplier-Divider modules

This module has 3 inputs, E1, E2, E3, and performs multiplication and division operations between these signals. It is configurable and allows to perform 3 types of functions. For our case study, the circuit is configured to carry out the operation:

$$S = \left[(E_1 - 1)\frac{KM}{KD}\right] + C$$

with

$$KM = \frac{a2 \pm k2(E2 - 1)}{4}$$

and

$$KD = \frac{a3 \pm k3(E3 - 1)}{4}$$

a2, a3 and C are tunable offset parameters, and k2, k3 tunable gain parameters. For our particular case study, the input E3 is not use.

The module is based on the RC4200 component of Fairchild Semiconductor, which is an analog multiplier designed to multiply two input currents (I_1 and I_2) and to divide by a third current (I_4). The output is also in the form of a current (I_3).

Unfortunately, we haven't found any Spice model of this component, or any equivalent reference. We have simply modeled this component as a current source, whose value is a function of current flowing in particular points. SPICE offers the CURRENTSENSE component to measure a current, such as an ammeter, and the CURRENT_GEN component as the current source (Fig.4).

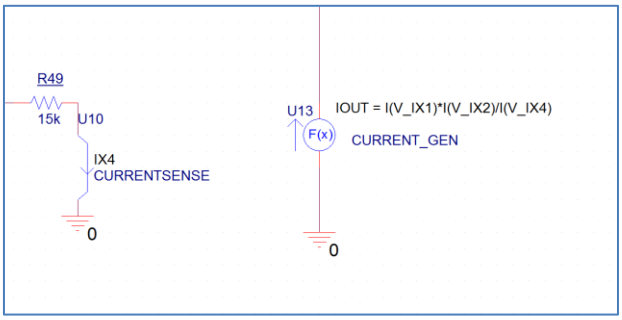

Fig.4 RC4200 simple model

Unlike the square root extractor module, this module must be configured according to its context of use. On-site maintenance agents use specific guidebook to configure and calibrate the module. We use the same procedure to configure the modeled module.

3.3 Functional chain model

The modeled modules have been integrated into a component library of the PSpise tool. For non-generic components, such as the multiplier-divider, we have declared the module set points (position of potentiometers, position of switches) as parameters. Thus, to model a particular functional chain, the user places these modules, as electronic components, and connects the inputs / outputs.

To simulate a transient, we used a piecewise linear voltage source: the evolution over time of the voltage is given in an external file. This allows us to simulate any transient

4 Analysis of the simulation

4.1 Module analysis

Our first analysis focused on each unit module. After module tuning and calibration phase, we launch a DC sweep simulation to check the module transfer function by varying the input voltages to their full scale (1-5V).

For the two modeled modules we did not have any convergence problems. This type of analysis makes it possible to estimate the error introduced by the module with respect to the expected mathematical function. And so improve the Simulink/Matlab models that we currently use to calculate theoretical values. Fig.5 represents the square root extractor module deviation (in mV) with respect to the calculation of the mathematical square root. The results are compatible with the supplier's technical manual:

- for inputs below 1.8V, the deviation in mV is [-208;12] for the supplier, and [-207.7;20.0] for the model
- for inputs above 1.8V, the deviation in mV is [-20;20] for the supplier, and [-11.0;13.9] for the model.

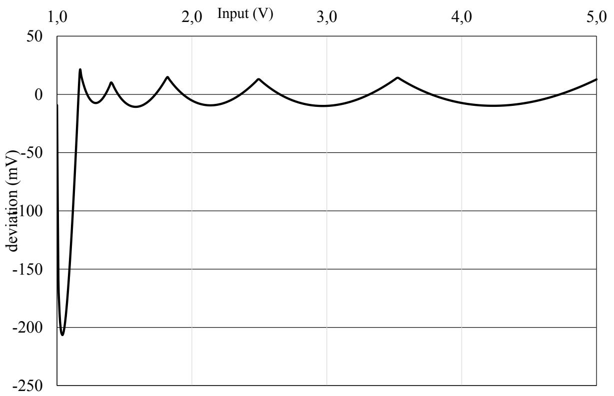

Fig.5 Deviation analysis

The impact of temperature on module behaviour has also been launched. The values found with the model are lower than the vendor data. This discrepancy can be explained by the fact that we have over-simplified the generation of internal power supplies (see section 3.1). To improve the accuracy of the model, in a future work, a specific study on the temperature impact on the generation part of the internal power supplies must be carried out.

4.2 Functional chain analysis

The analysis of the case study was made by connecting the different modules used in the functional chain (see section 3.3). For the transient, we used the Microsoft Excel tool to generate the values of the input voltage (Water Flow input of Fig. 1) as a function of time, with a step of 10 ms. The voltage curve is identical to that generated by the test tool on the plants (Fig.2).

As mentioned in section 2.3, we were not able to model the relay module of the 9020 system because at the time of the study we did not have all the electronic components references. To ease analysis, we have modeled the threshold relay with a voltage-controlled voltage source: The difference at the inputs of the relay drives the voltage source, its gain is 1. This Voltage-Controlled Dependent Source is connected in series with another fixed voltage source, corresponding to the theoretical switching voltage of the relay (1.26V in our case study). Thus, when the sum of these two voltages is zero, this corresponds to the relay switching.

The PSpice tool offers measurement expressions to evaluate the characteristics of a waveform. A measurement expression is made by choosing the waveform and the waveform calculation you want to evaluate. For the case study we use the zerocross measurement.

For the transient selected, the expected values are as follows, without taking into account of the relay switching time:

- the relay switches theoretically 29.076s after the start of the transient;
- the switchover must be in interval [28.662s;29.591s].

A transient analysis at the reference temperature (27 °C) shows that the chain switches to 29.06361s. This value is close to the expected theoretical value.

An impact analysis of the temperature was carried out, varying the temperature between 0 °C. and 60 °C. in steps of 10 °C. The results show that, over this temperature range, the impact of the temperature on the response time is of the order of 40 ms. The response time is always within the tolerance range. The Fig.6 shows the variation of the response time with respect to the expected theoretical value.

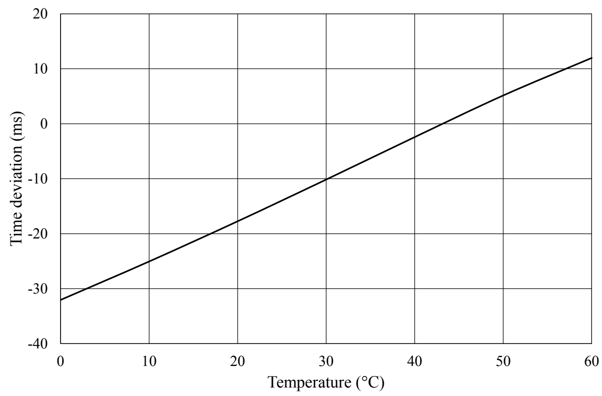

Fig.6 Temperature impact on response time

However, this first impact analysis needs to be refined. Indeed, as indicated above, the internal power supplies are too simplified, and the temperature impact on the passive components (resistor, capacitor) must be specified.

5 Conclusion and Perspectives

This first study showed the feasibility and the interest of using low level models to simulate the behavior of perennial systems. Current processing capabilities enable complex systems to be simulated on a desktop computer: For our case study, the computation time of the transient analysis was realized in real time (35 s of simulation for a transient of 35 s).

The temperature impact analysis or the module's transfer function analysis provide data to improve the accuracy of the high-level functional models (based on Simulink/Matlab) currently used by EDF and its suppliers.

However, this requires to finely model all the module's components. In particular, the behavior of the internal power supplies as well as to identify the temperature coefficients of the various passive components. Indeed, depending on the technology used for these components, the impact of the temperature is different. In Spice, for a resistor the change in its nominal value due to a change in temperature is defined as:

$$R = R_{nom}(1 + TC1(T - T_{nom}) + TC2(T - T_{nom})^2)$$

where R_{nom} is the nominal value of the resistor at the reference temperature T_{nom}, TC1 and TC2 are respectively the linear (in ppm/K) and quadratic (in ppm/K^2) temperature coefficient. In our modules, some resistors have negative and other positive linear coefficients.

Another contribution of using models at electronic component level is to run sensitivity analysis. Sensitivity identifies which components have parameters critical to the measurement goals of a module or functional chain. As described above, the 9020 modules must be adjusted with potentiometer to fulfill the expected function. This operation is delicate and long. The sensitivity analysis on the potentiometer settings identifies which potentiometers are the most influential on the behavior of a module or a chain. This allows the maintenance operator to concentrate on the most important potentiometers during the calibration procedure.

Finally, one another use is foreseen. By comparing measurements at particular board points with those given by the model, it is possible to make sure that the module is well configured and on the other hand can make it possible to identify drifts that report future failures. This theme will be studied in the coming years.

References

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