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CONCEPTUAL DESIGN AND DEVELOPMENT OF AN AUTOMATED CO-GENERATION SYSTEM

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Abstract

Co-generation or Combined Heat and Power (CHP) is the simultaneous generation of both electricity and heat from the same fuel for useful purposes. The fuel varies greatly and can include coal, biomass, natural gas, nuclear material, the sun or heat stored in the earth.

Co-generation (as a vector of energy efficiency) and renewable sources of energy possess their own set of low carbon benefits. Coupling co-generation and renewable sources contribute to a very strong proposition since it leads to the supply of both low-carbon electricity and low-carbon heat. In the case of co-generation plants fuelled by renewable energy sources, the low-carbon benefits of the heat are obvious since they derive from the renewable nature of the fuel. However, this also apply in the case of plants feed by other types of fuel. Such plants produce excess heat alongside electricity. When this heat, which is an unavoidable by-product, is used to satisfy an existing heat demand carbon dioxide (CO_2) emissions are reduced overall, through a more efficient use of the fuel. The distributed generation systems produce energy close to the point of use, which typically doubles the efficiency in terms of fuel input-to-energy output ratio compared to conventional power generation in central plants. This means that the same amount of energy can be produced with half the amount of fuel, making distributed generation an effective approach to reducing greenhouse gas emissions. According to official government reports, the creation of distributed generation systems will account for at least 5% of gas reduction.

In this paper the conceptual design and development of an automated co-generation system to apply in collective residences is presented. After concluding the definition of the demanded specifications and requirements for the co-generation system it is presented and discussed the developed solution with the identification of the main components, including the selection and prototype implementation of the necessary sensors and actuators that integrate the system. It is also shown a systematized approach that consists in using the GEMMA and the SFC formalisms for the structure and specification of all the system behaviour, considering all the stop states and functioning modes of the co-generation system.

Keywords

Co-generation, Mechatronic Design, Controllers Design, GEMMA, SFC

Introduction

At the present time, industries, collective buildings, private houses, etc., need continually more and more electric power and thermal energy. Usually, the necessary electric power is supplied by the national electric network of energy, that uses biomass, fuel oil, liquefied petroleum gas, and more recently in Portugal, natural gas as thermal sources of energy.

The use of the energy sources is not always the most correct and efficient, due to the way the combustion of fuels is made and to the great losses during distribution. The reduction of costs of an exploration (whatever the type) considerably depends, on the efficient use of the energy. In order to improve the energy efficiency of the facilities, many studies have been carried out that lead to great progresses in the improvement of that condition. Cogeneration or combined-cycle power station appears as a very interesting technology because it allows a great saving of energy and consequent reduction of costs.

In a conventional thermal power plant, no matter how efficient it is, most of the energy contained in the fuel used to power the turbines is transformed in heat that is lost for the adjacent areas. In general, these thermal power plants convert only about 35% (approximately 1/3) of the energy of the fuel in electric energy. The remaining 65% are losses (under the form of heat). The cogeneration of electric power and heat also appears as a way of changing this situation, increasing the energy efficiency of the process, close to 85% of the energy contained in the fuel. This way, more than 4/5 of the fuel chemical energy is converted in usable energy, resulting in economical and environmental advantages.

Figure 1 shows the energy balance between a traditional system and a cogeneration system [1].

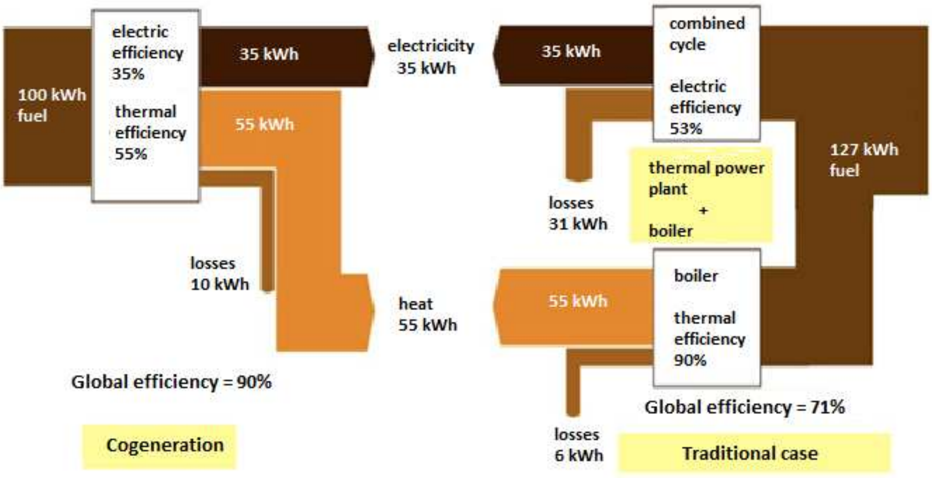

Figure 1 - Energy balance of traditional and cogeneration systems [1]

Cogeneration is defined as being a production process with combined use of heat and electricity, which results in the use of more than 70-80% of the fuel thermal energy of the process. However, usually, its use is only suitable in situations where the annual equipment operation exceeds 4500 hours. Figure 2 shows in a schematic way a typical cogeneration unit.

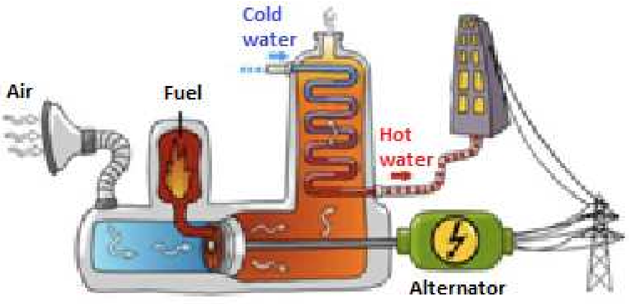

Figure 2 - Typical outline of a combined-cycle power station [2]

The main advantages of the use of cogeneration can be pointed out as the following [3, 4]:

- Reduction of the consumers' dependence;
- Reduction of fuel consumption, and consequently, energy bills;
- Reduction of noxious gases emissions, avoiding the need to decrease the greenhouse gas emissions;
- Decentralization of the energy production;
- Reduction of the nuclear and hydroelectric energy production;
- Increase of the reliability of the energy supply;
- Increase of the stability of the electric system.

The potentials users of cogeneration units are facilities with the following characteristics [5]:

- Simultaneous and continuous need of thermal and electric energy;

- Operation period of at least 4500 to 5000 hours/year;
- Residual heat available with high quality;
- Availability of quality fuels;
- Enough space and appropriate location for the equipment implementation.

It is verified that these characteristics are found with more frequency in the manufacturing industry than in collective buildings. However, the technological advancements verified in the design and development of cogeneration equipments has been making them alternative options to the production of energy in collective buildings, both residential or offices. In the latter the main thermal needs are for heating, ventilation, air-conditioning and sanitary hot waters; in industry the needs are also for heating, ventilation and air-conditioning but also steam and hot water for several uses.

Previously to the implementation of a cogeneration system it is of fundamental importance to perform a good estimation of its thermal efficiency and economic viability. This is an important productive factor. The optimization of the thermal efficiency will help to define a system where certain costs, dictated by thermodynamic options, can be justified for the minimization of the overall involved costs.

When considering electric power, the main question is to determine which will be the best way of obtaining that energy, respecting certain imposed conditions, namely in environmental terms, economical investment, equipments maintenance and production capacity. The objective of the optimization consists in the use of numerical techniques of non-linear optimization to find the values of the variables of the thermal system (temperature, pressure, dimensions and efficiency of the equipments) that minimize the costs of installation of the system. They are usually divided in capital costs, operation costs and maintenance costs (including fuel) of the system [5].

Case study

The case study that was considered to carry out this research work is related to a hotel with the following characteristics: 81 rooms, occupancy rate of 78%, average electric consumption of 32504 kWh/month and a maximum heating consumption of 170550 MJ/month. Through the annual consumption of natural gas the waveform of thermal power was drawn, as it can be observed in the figure 3.

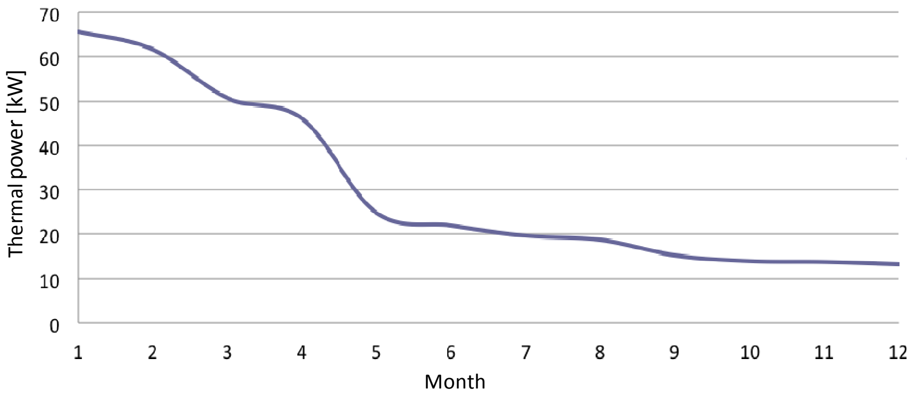

Figure 3 – Case study: annual thermal power consumption

After obtaining the thermal power consumption, it was necessary to select the cogeneration system that better adapted to the case. Two options were considered: cogeneration system working for twelve months (table 1 and figure 4); cogeneration system running for six months (table 2 and figure 5). Whatever the option, use of the cogeneration for six months or twelve, an auxiliary boiler would always to be used as the cogeneration system would only guarantee part of the energy needs. The boiler would work as an auxiliary system to guarantee the supply of the remaining thermal energy when necessary, and also as an emergency system in case of flaw of the main system.

Table 1 – Main parameters of the first option for the case study (1 year)

	Thermal power [kW]	Functioning mode
Cogeneration system	< 13	12 months
Boiler	< 52	in parallel

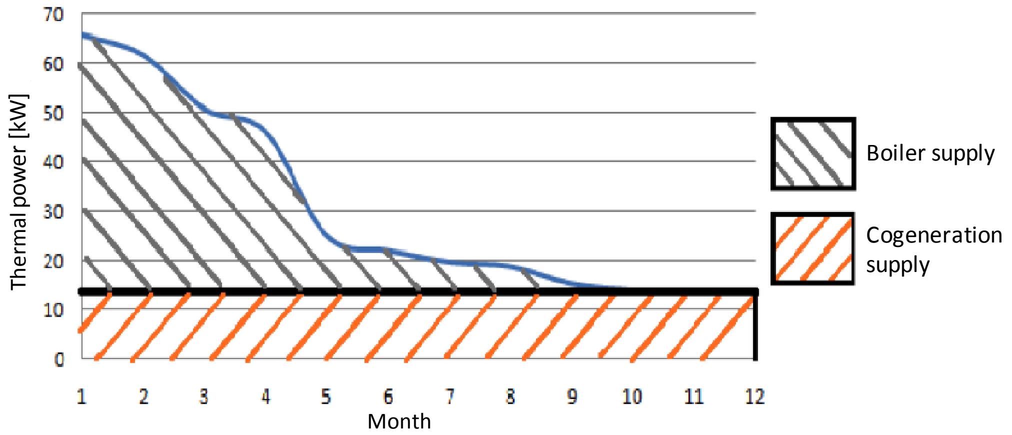

Figure 4 – Thermal power consumption and operation level of the cogeneration system (1 year)

Table 2 – Main parameters of the second option for the case study (6 months)

	Thermal power [kW]	Functioning mode
Cogeneration system	< 23	6 months
Boiler	< 42	in parallel

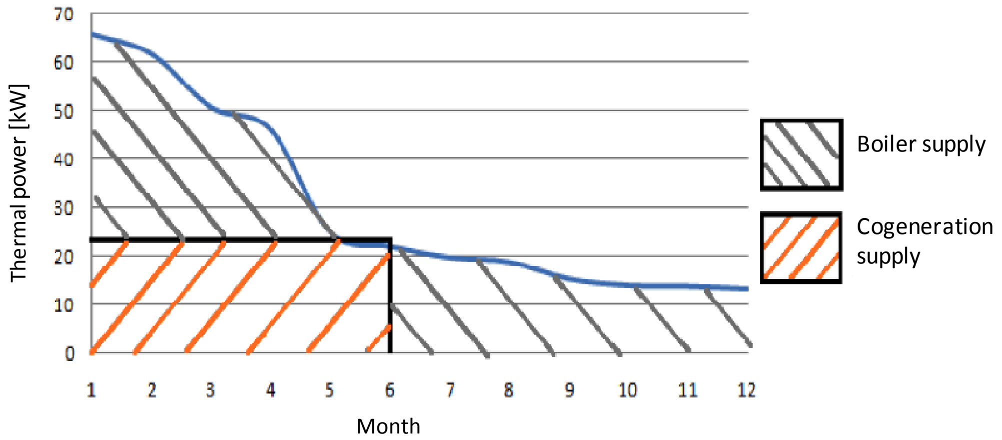

Figure 5 – Thermal power consumption and operation level of the cogeneration system (6 months)

From the optimization study of the thermal and economic efficiency, the two options were compared; As a result the second option was selected after demonstrating to be the most economical solution. Next, a description of the components to be used was made, as well as the operation modes considered. The system consists of the following essential components: cogeneration system (micro turbine), auxiliary boiler and tanks. Figure 6 shows the layout of the installation.

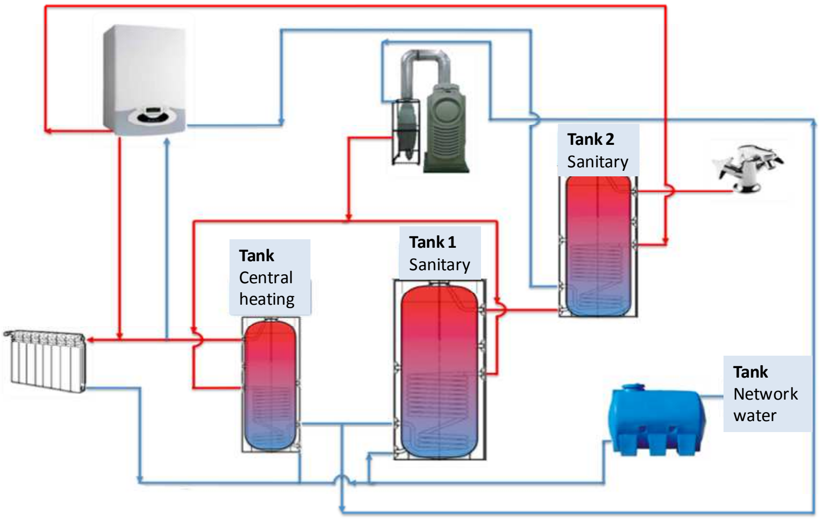

Figure 6 – Layout of the developed installation

According to the thermal economic study, it was defined that the cogeneration system would have to cover 35% of the maximum needs of the hotel. The selected system was a micro turbine of low pressure natural gas with a thermal power of 28 kW, associate to a heat exchanger of no mixed crossed flows.

In this case the boiler would work as one of the main components, being operational during the 12 months of the year, unlike the cogeneration system that would be just for 6 months. The selected boiler must have a thermal power of about 42 kW, in agreement with the previous study. The selection was a natural gas boiler of 45 kW.

According to figure 6, the installation has four water tanks: one for the mains water supply, other for the central heating and other two for the sanitary hot waters. The mains tank serves as storage for the case of flaw of mains water supply; the central heating tank would be used to make the heat exchange of the cogeneration system, from the liquid that circulates in the coil with the water of the central heating; while the tanks of sanitary water would be to make the heat exchange from the cogeneration systems (tank 1) and boiler (tank 2) with the sanitary waters.

Process control

The automatic control is designed with the objective of controlling the thermal power according to the thermal energy needs of the hotel. The control is to be automatic, therefore meaning the need to select sensors, actuators and the respective control unit (PLC - Programmable Logic Controllers). The control flow of the process variables is described in the figure 7. On the other hand, figure 8 shows the layout of the developed installation with the incorporation of the main actuators and sensors. Two main sensors types were used, one to measure temperatures (S1, S2, S3, S4, S9, S10 and S11) and the other to measure liquid levels (S5, S6 and S7). Four water pumps (P1, P2, P3 and P4) were considered and fourteen solenoid valves (V1 to V14).

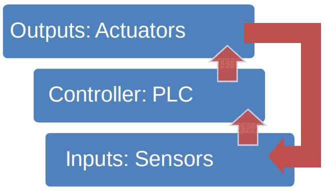

Figure 7 – Control flow of the process variables

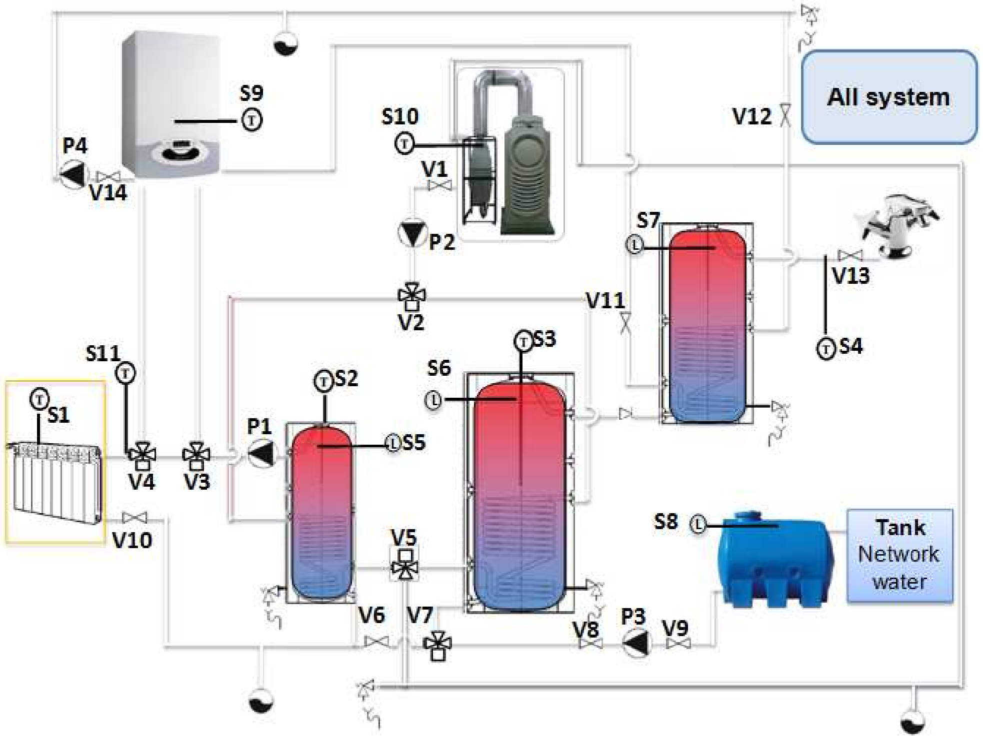

Figure 8 – Layout of the installation with actuators and sensors

Controller structure

A good performance of the process control is of maximum importance. From the desired specifications up to the implementation of a controller program for an automation system, the designer needs to use some different and complementary formalisms and tools that help him in all the necessary steps. Taking into account aspects related to systems' dependability, the designer must be able to use these formalisms and tools together in order to achieve the desired behaviour for the system. There are many formalisms and tools to help the designer during the process. For the structure of the controller it is possible to use GEMMA [6], Multi-Agent formalisms [7] ; for the specifications Petri Nets can be used [8], SFC [9], Statecharts [10], UML [11]; for the implementation, the Programmable Logic Controllers (PLCs) [12], Industrial computers [13], Microprocessors "Brusamolino et al. (1984)", and others. Currently there are some suitable formalisms for the development and creation of the structure and specification of an automated production system controller. Between these formalisms the GEMMA (Guide d'Étude des Modes de Marche et d'Arrêt) [6] and SFC (Sequential Function Chart) [9], both developed in France, appear to be the stronger. GEMMA is well adapted to define the controller structure and SFC is well adapted to the complete controller specification. GEMMA is a method that, on the basis of a very precise vocabulary, proposes a simple structured guide to the designer, based on a graphical chart that contains all the run and stop modes, or states that a machine or an automated system can assume. In the graphical chart GEMMA these run and stop modes, ways or states of the Plant are divided in three main groups: States "A"- Stop states; States "D"- Failure ways States; and, "F"- Running ways.

In the present case study, in order to obtain the total SFC controller, which includes all the operation modes required for the correct operation of the system, the graphic chart GEMMA was used because it allows the definition of the run and stop machine tasks. Figure 9 shows the GEMMA graphic chart developed for the presented case study. The considered tasks are described as follows:

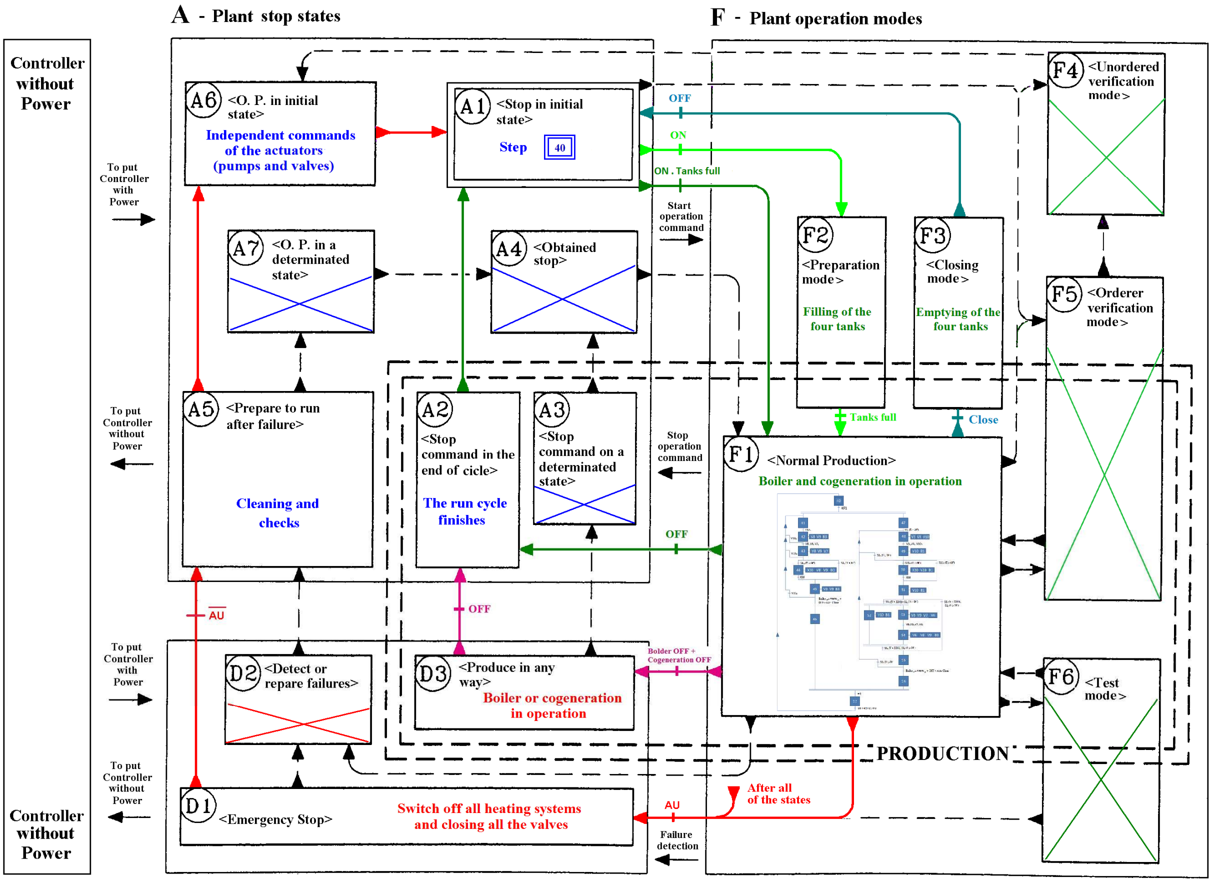

Figure 9 - GEMMA of the plant controller

A1 – “Stop in the initial state” represents the state of the turned off system. The tanks can be full or not, as well as the water can be to the required temperature or not;

F1 - Coming of the task A1, when the start command of the machine occurs, it happens the change for the task F1 "Normal production” (heating water for central heating and sanitary purposes). As an example, figure 10 presents the SFC specification for this task;

A2 – When happens the stop command of the machine the run cycle finishes in agreement with the condition described at the task A2 “Stop command in the end of cycle”;

F2 – “Preparation mode” the tanks will be full and their water temperature will be put in the desired level;

F3 – “Closing mode” allows the reverse operation, that is, the progressive stop of the system with emptying of the tanks;

D3 – Due to maintenance, technical breakdowns or other situations it can be necessary to switch off the heating systems (boiler or cogeneration micro turbine). This way allows that the system only uses one of the heating systems, while the other could be temporarily inoperable; this is the main purpose of task D3 "Production in any way";

D1 – In case of an emergency (press button AU), task D1 “Emergency stop" is executed. This switches off all heating actions and closes all the solenoid valves. Finally, the AU button (emergency stop) allows passing to task D1 starting from all of the tasks;

A5 – After the emergency stop (task D1), the cleaning and the verification are necessary. This is the purpose of task A5 "Prepare to run after failure“;

A6 – After the procedures of cleaning and verification are finished it becomes necessary to perform the return to the initial task of the system, as described at the task A6 "O.P. (operative plant) in the initial state".

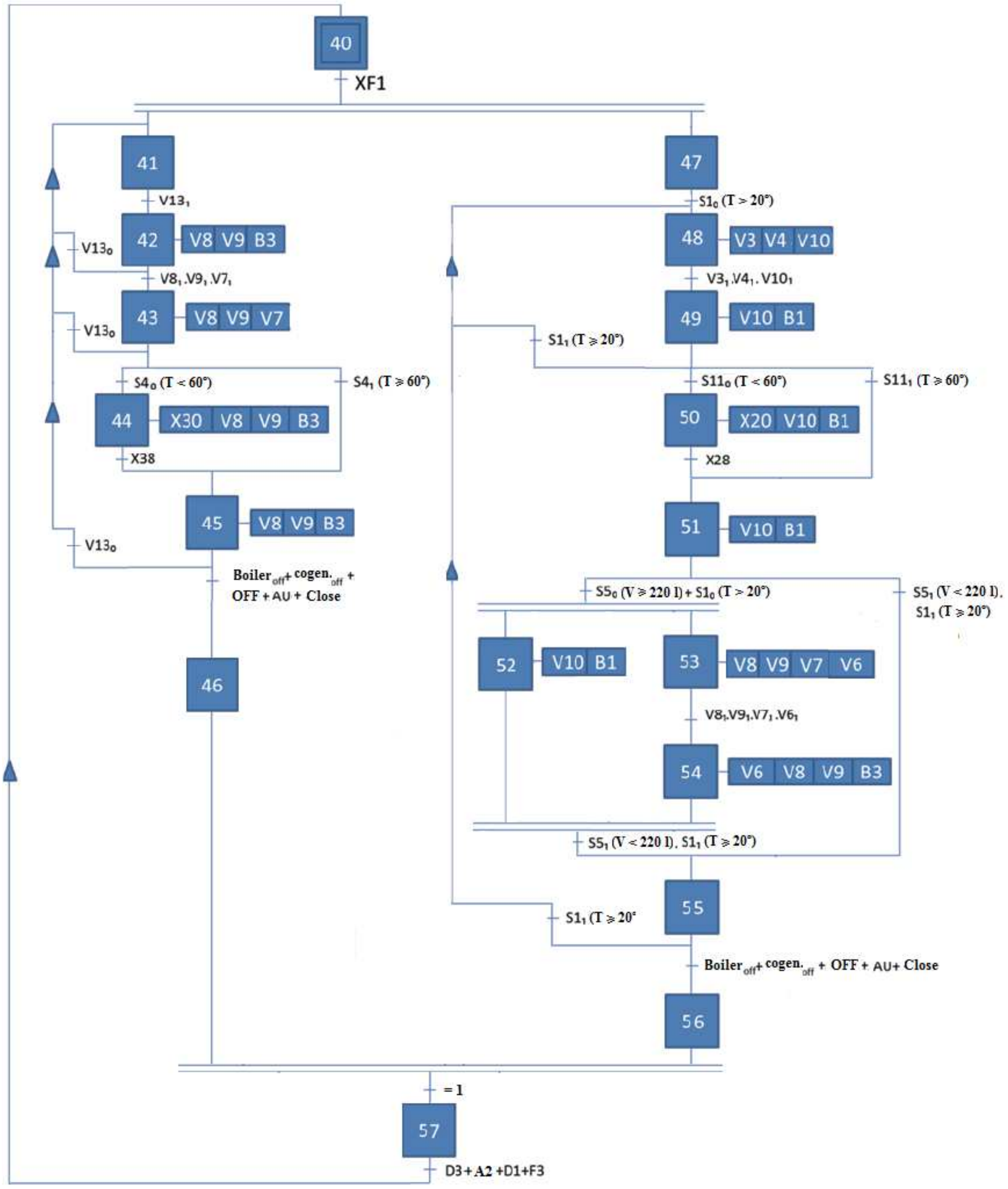

Figure 10 – Example of a Low level SFC specification for task F1 “Normal production”

The implementation of total controller's specification, based on GEMMA and presented in figure 9, was carried out using the Vertical Coordination that is based on the following main stages:

1 – Elaboration of a high level SFC that directly translates the base GEMMA of the system behaviour;
2 - Elaboration of multiple low level SFCs corresponding to each one of the GEMMA tasks;
3 - Synchronization of the SFCs using the vertical coordination method.

Only the more relevant parts are presented here, the GEMMA, which corresponds to the high level SFC, and one low level SFC corresponding to the F1 task (figure 10). Elsewhere there is a publication specifically dedicated to this subject, of the same authors of this paper [15], that presents and discusses a case study with the aim of application the vertical coordination implementation of total controller's specification based on GEMMA.

All the controller specification of this developed system was simulated on Automation Studio Software. The obtained results led to the conclusion that all the requirements defined on the Emergency Stop Standards, were accomplished.

Conclusions

It has been presented in this paper in detail the conceptual design of an automated co-generation system including the adopted techniques for the deduction of complex specifications for dependable automation systems.

This way, it was explained the use of the GEMMA and the SFC formalisms for the structure and specification of all the system behavior, considering their stop states and functioning modes. Also, the vertical coordination implementation of a complex total controller's specification, based on the GEMMA graphical chart, was also presented.

The obtained results, by simulation with Automation Studio software, show that the adopted approach is adequate.

Further work will be devoted to the application of formal methods to verify some important system's behavior properties (taking into account the discrete behavior of the system) and, in other hand, the application of modeling techniques for hybrid systems and respective tools for simulation and formal verification.

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