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Controller synthesis of multi-energy system for autonomous domestic water supply

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ABSTRACT. The continuous development of ICT facilitates the emergence and rapid proliferation of a wide variety of low-cost processors for the execution of programs in complex embedded applications. In this paper, the study explores the possibility to benefit from this wealth of computing capacity at a reasonable cost to solve concrete problems encountered in developing countries, particularly in water and energy supply . . . The problem to be solved in this work is to achieve around a microprocessor, the central control body that ensures the coordination of the operation of discrete event systems according to functional requirements described by the user. For this, we propose an automatic generation tool of program control for different microprocessor targets taken from the functional design specification of the system given in a Grafcet form. To put it in evidence, the proposed case study is focused on the specific problem of domestic water supply, considering several water resources, several energy sources, several pumping mechanisms and multilevel hierarchical priority access to water.

RÉSUMÉ. Le développement vertigineux des TIC favorise l'émergence et la prolifération rapide d'une grande variété de processeurs à bas coût destinés à l'exécution de programmes embarqués dans des applications complexes. Dans ce papier, l'étude explore la possibilité de tirer profit de cette profusion de capacité de calcul à cot raisonnable pour résoudre des problèmes concrets que l'on rencontre dans les pays en développement, notamment ceux d'approvisionnement en eau et en énergie, . . .Le problème à résoudre consiste à réaliser autour d'un microprocesseur l'organe central de contrôle qui assure la coordination du fonctionnement de tout système à événements discrets suivant un cahier des charges qui est spécifié par l'utilisateur. Pour cela, nous proposons un outil de génération automatique de programme de contrôle pour différentes cibles à microprocesseur à partir d'une spécification fonctionnelle sous la forme d'un Grafcet. Pour le mettre en évidence, le cas d'étude proposé est focalisé sur le problème spécifique de l'approvisionnement en eau domestique, en considérant plusieurs ressources d'eau, plusieurs sources d'énergie, plusieurs mécanismes de pompage, ainsi que plusieurs niveaux hiérarchisés de priorité d'accès à l'eau.

KEYWORDS : ICT, developing countries, water & energy supplying, Grafcet modeling, automatic synthesis, logic controller.

MOTS-CLÉS : TIC, pays en développement, approvisionnement en eau & énergie, modélisation Grafcet, synthèse automatique, contrôleur logique.

1. Introduction

The evolution of Information and Communication Technologies has greatly facilitated many domains, such as health care, education, commerce, etc. The automation is considered one of the most important sectors which has remarkably been developed thanks to the ICT revolution. For example, almost all digital devices, used to control automated electromechanical systems in industries are nowadays based on sophisticated small microcontrollers instead of hard wired logic components (such as relays, cam timers, drum sequencers), that contribute explicitly to save time, energy, materials and money. Despite all these available advantages, developing countries are slow to benefit from these to solve their problems, such as energy and water distribution issues. For example, in 2013 Cameroon National Institute of Statistics (INS) declared that “almost 92% of households in Yaound suffer from intermittent water cuts.” “To reduce the shortages, households depend on the following sources: public water supply (55%), mineral water (10%), drilled wells (6%) and other undrinkable water sources (29%).” [5]. Moreover, conveying water to households may require electric power. Unfortunately, the urban power distribution network does not have complete geographical coverage of Yaound and it hardly guarantees the continuous presence of energy in the covered areas. The solution proposed in [6] is to invest on renewable energy sources, such as solar energy, wind energy, etc.

Therefore, the objective of this paper is to benefit from ICT tools in order to study and realize a complete and autonomous system for water and power supply. This smart system guarantees to continuously provide water to households, and it automatically switches between several water & power resources according to the source availability and the service costs. Concerning ICT tool applied on the automation applications, International Electrotechnical Commission (IEC) has issued five standard programming languages: Ladder Diagram, Functional Block Diagram, Sequential Function Chart (or Grafset), Structured Text and List of Instruction Sets [8]. Grafset, a specification and graphical programming language of industrial automation systems [4], is considered as one of the most used specification languages nowadays.

Many research and development (R&D) works are carried out to promote and popularize this language, such as UniSim editing environment tool ([1], [9]) and PLCopen XML tool [10]. On the other hand, the Grafset language has actually been built and developed to design programmable logic controllers (PLC) devices ([1], [3], [11]). PLC are digital devices basically used to control automated electro-mechanical systems in industries. They are specially designed to survive in harsh industrial situations and could not be recommended for other simpler control applications. Hence, they are relatively expensive for developing countries and are not required to be operated in corresponding environments. Therefore, our research on Grafset Synthesis have permitted to carry out a novel software tool that permits to automatically convert any Grafset specification code to bin-stream module and deploy it on economic microcontrollers. This tool is exploited in this case study to generate the appropriate solution once the system is well specified in Grafset language.

The paper is organized as follows: Section 2 presents the functional design specification of an autonomous water & energy supply system; the corresponding Grafset model is explained in section 3. The solution synthesis to obtain an automatic control system is developed in section 4 and conclusions are drawn in section 5.

2. Functional Design Specification (FDS)

In this section, we will describe the physical layout architecture of water & energy supply system and its synthetic scheme.

2.1. System Features

Figure 1 illustrates the water distribution system for a six-floor building, consisting of: several water sources, several sources of pumping energy, several water access gates with different priority levels, control system, in addition to two water tanks: the main tank T_1 and the secondary tank T_2 .

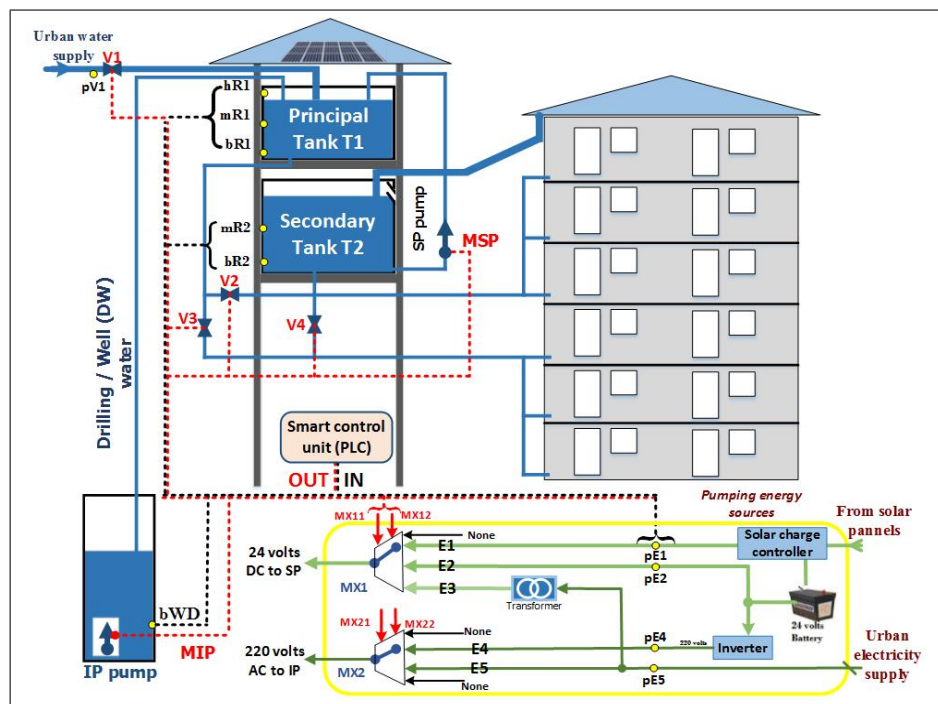


Figure 1. Synthetic diagram of the system

2.1.1. Three water sources

Supposing that we have three water sources mentioned below. These will be used to serve all domestic uses, except for instant consumption:

1) **Urban network water distribution:** realized by a public or private company. In this case of the study, we assume that the urban network system guarantees to furnish sufficient pressure to propel water to the roof at tank T_1 , without a need for any auxiliary pumping equipment.

2) **Well Water:** costs less than the first source once it is realized. The immersed pump IP is used to pump the water up to the tank T_1 . In this paper, we consider that well water is already treated and pure; otherwise water refinement could be achieved by using

an intermediate tank.

3) **Reserve of rainwater:** collected from a roof or other catchment area and held in the tank T_2 . It is considered the cheapest water resource. It can directly serve the first three floors via the gate **V4**, and indirectly serve the rest of the floors by means of the surface pump SP, which permits to pump the water from the rainwater tank T_2 up to tank T_1 .

2.1.2. Five sources of pumping energy

The water pumps require a power supply providing either 24 volts or 220 volts to operate. Hence, we consider the following electrical power sources:

- 1) Source **E1**: is 24 volts solar panel.
- 2) Source **E2**: is 24 volts battery, can be charged with solar power.
- 3) Source **E3**: is 220 volts ac to 24 volts dc transformer, from Source **E5**.
- 4) Source **E4**: is inverter generator, provides 220 volts.
- 5) Source **E5**: is public electricity network, provides 220 volts.

2.1.3. Two pumping mechanisms

1) The surface pump SP is setup for 24 volts DC; the power supply is provided either by direct solar panels **E1**, or by solar charged battery **E2** or by transformer **E3**. SP permits to pump the water from T_2 up to T_1 .

2) Immersed pump IP is setup for 220 volts; the power supply is provided either by the inverter **E4** or by the urban network **E5**. IP permits to pump the well water up to T_1 .

2.1.4. Four water access gates

These gates are associated with the logic control system which leads automatically the gate opening & closing process in order to select the adequate water path from water source to faucet via T_1 or T_2 tanks:

- 1) **Gate V1**: drives water from urban distribution network to T_1 . It closes whenever T_1 is full to avoid water losses.
- 2) **Gate V2**: drives water from tank T_1 to the highest three floors. It is open as long as water is available in T_1 .
- 3) **Gate V3**: drives water from tank T_1 to the lowest three floors. It is open only when the water level in T_1 is above the lowest level **br1**, and the water level in T_2 is below the middle level **mR2**.
- 4) **Gate V4**: drives water from tank T_2 to the lowest three floors. It is open only when the water in T_2 is above the middle level **mR2**.

2.2. System Overview

A domestic water supply station comprises two tanks T_1 and T_2 , three water supply sources, five electricity sources, two tanks, two pumps, many gates and a smart control system, as shown in Figure 1.

Filling process of tanks T_1 & T_2

Filling process of T_1 occurs when the water level in it is less than the middle level $mR1$ ($mR1 = 0$), the filling process stops as soon as T_1 becomes full ($hR1 = 1$) to avoid water losses. The tank T_1 is supplied with water by using one of the following sources, ordered from highest to lowest priority:

1) Pumping the water from the tank T_2 by the means of PS; provided that T_2 is not empty ($bR2 = 1$) and there is sufficient 24 volts power to run PS ($pE1 = 1$, $pE2 = 1$ or $pE5 = 1$); otherwise we will deny this process and move to the lower priority process.

2) Pumping the water from the drilling well by means of IP; provided that drilling well is not empty ($bWD = 1$) and there is sufficient 220 volts power to run PS ($pE4 = 1$ or $pE5 = 1$); otherwise we will deny this process and move to the lower priority process.

3) Conveying the public network water by opening the gate $V1$; provided that this source is available ($pV1=1$); otherwise this process is denied.

While the tank T_2 is supplied only with rain water, when it is raining profusely and the tank becomes full, the rainwater surplus is poured outside through the exhaust outlet.

Water Circulation from tanks to the building

The lowest three floors are supplied with water either from tank T_2 or from tank T_1 , respecting the following priority order:

1) **Highest-priority path:** the water is conveyed from the rainwater tank T_2 to the floors by means of opening gate $V4$ and closing gate $V3$, provided that the water level in T_2 exceeds $mR2$ ($mR2 = 1$); otherwise there will not be sufficient water pressure in pipes to serve these floors.

2) **Lowest-priority path:** the water is conveyed from the tank T_1 to the floors by means of opening gate $V3$ and closing gate $V4$, provided that the water level in T_2 is below $mR2$ ($mR2 = 0$).

Gate switching process

Each gate is electrically controlled and has two positions: Open & Closed to permit or preclude the water to flow through it respectively, symbolically the Open state is represented by the logic signal 1; while the Closed state is represented by 0:

– The gate $V1$ is open ($V1 = 1$) only when the water level in T_1 is less $mR1$ ($mR1 = 0$), the urban water source is available ($pV1 = 1$) and all other water sources are denied, $V1$ stays open until T_1 becomes full ($hR1=1$) or the urban water resource is stopped ($pV1=0$).

– The gate $V2$ stays open ($V2 = 1$) as long as the water level in T_1 is above $bR1$ ($bR1 = 1$), and closes in the opposite case ($bR1 = 0$).

– The gate $V3$ stays open ($V3 = 1$) only when the water level in T_1 is above $bR1$ ($bR1 = 1$) and the water level in T_2 is below $mR2$ ($mR2 = 0$); otherwise it closes ($bR1 = 0$ or $mR2 = 1$).

– The gate $V4$ stays open ($V4 = 1$) only when the water level in T_2 is above $mR2$ ($mR2 = 1$), and closes in the opposite case ($mR2 = 0$).

While the highest three floors are directly supplied with water from tank $T1$ by opening the gate $V2$.

Pumps energy supply

Before running the pump SP , we must make sure that one of the three energy sources $E1$, $E2$ or $E3$ is supplied ($pE1= 1$, $pE2 = 1$ or $pE5 = 1$), where the multiplexer switch

*MX1 selects the available source taking into account the priority rules (that the source **E1** is prior to **E2** which is prior to **E5**). Once the power is drawn from the selected source, **SP** can be turned on ($MSP = 1$). **SP** is immediately stopped ($MSP = 0$) if none of the corresponding sources (**E1**, **E2** or **E3**) is accessible.*

*It is the same for the pump **IP**: the required energy to operate **IP** is provided by one of the two sources **E4** or **E5**, where the source **E4** is prior to **E5**. The selection between them is achieved thanks to the multiplexer switch **MX2**. $MIP = 1$ permits to turn on the **IP** pump. For security reasons, each time a pump is running it must continuously operate for 20 seconds at least.*

2.3. The switching process between water & energy sources

The switching process between water sources is well managed by activating/deactivating the gates control.

Concerning the switching process between sources of pumping energy, it is necessary to use another electronic component that can be electrically controlled. Multiplexers are appropriate. The surface pump **SP** is supplied either by **E1**, **E2** or **E3**. The selection of the desired source among them can then occur by means of a multiplexer switch **MX1**. The immersed pump **IP** is supplied either by **E4** or **E5**. Also, the selection of the desired source among them can then occur by means of a multiplexer switch **MX2**.

Table 1 shows that **MX1** has two control inputs (**MX11** and **MX12**), which are used to select which input source (among **E1**, **E2** and **E3**) to connect with the output line to supply **SP**. While **MX2** also has two control inputs (**MX21** and **MX22**). They are used to select which input source (between **E4** and **E5**) to connect with the output line to supply **IP**. **MX11**, **MX12**, **MX21** and **MX22** are then outputs of the smart control system.

MX1 (For SP pump)			MX2 (For IP pump)		
MX11	MX12	Connection of	MX21	MX22	Connection of
0	0	None	0	0	None
1	0	E1	1	0	E4
0	1	E2	0	1	E5
1	1	E3	0	0	None

Table 1. Truth table of **MX1** and **MX2** multiplexers

2.4. The logic control system

The water distribution system is completely controlled by a smart control system (controller). It has its proper power supply that makes it autonomous.

The input points of the controller are connected to sensors, which permit to report events and transmit this information as signals to the controller. The 11 digital input sensors used in our system are summarized as follows:

- Water level sensors (**bR1**, **mR1**, **hR1**, **bR2**, **mR2**, **bWD**)
- Pressure sensor (**pV1**)
- Electrical power sensors (**pE1**, **pE2**, **pE4**, **pE5**).

The controller will then read and analyze the input signals and generate actions to take upon encountering particular input signals. These generated actions are interpreted as output signals transmitted to output devices (such as actuators and relays) to control the water circulation system. The 10 digital output devices used in our system are :

- Inductors (**MIP, MSP**),
- Relays (**V1, V2, V3, V4**)
- Inputs of multiplexer switches (**MX11** and **MX12** for MX1 multiplexer to select either E1, E2 or E3 pumping energy sources; and **MX21** and **MX22** for MX2 multiplexer to select either E4 or E5 pumping energy sources).

The Input/Output model of that logic control system is presented on Figure 2.



Figure 2. Input/Output model of the logic control system

3. Grafcet specification

From the physical layout architectural water supply system (as shown in Figure 1), we can describe several functional requirements of systems considered in particular contexts. In addition to the case of the whole system, some interesting systems may be obtained considering the fact that there is the absence of one of the following functions: urban electricity supply, drilling/well, urban water supply or battery. In this section, our attention is focused on the whole system. Initially, let's look at an overview of the Grafcet modeling language.

3.1. A brief background on the Grafcet language

The Grafcet (Graphe Fonctionnel de Commandes et d'Étapes/Transition), a graphic language for modeling automated systems, is the most international formalism used for high-level description of complex sequential systems [4]. It is widely used in several do-

mains such as home automation, automotive, power generation, manufacturing, etc. A grafcet specifies the behavior of a logic control system. This language has been standardized by the International Electrotechnical Commission IEC 60848 [2], and is understandable and readable compared to other specification languages as Petri net, Relay ladder, Instruction list, etc.

A grafcet is a graph that consists of two types of nodes: steps and transitions. A step is represented by a square, while a transition is represented by a horizontal line. The initial steps have a double square. Directed edges are necessarily used to connect steps to transitions or transitions to steps. Each step may be associated with several actions which represent the outputs of a Grafcet graph. An action is symbolized by a rectangle which is connected to a step. Its evolution from the initial state is done by firing transitions according to the Grafcet interpretation algorithm presented in [4], which is based on five evolution rules. They enable the calculation of the subsequent state and the corresponding output signals caused by an input event.

A grafcet model can be realized on programmable controllers (such as microcontrollers or FPGA). However, they do not allow a direct implementation on control targets like microcontrollers, which cost comparatively less than FPGAs. For this, we have conducted research on the automatic and robust synthesis of logic controllers specified in Grafcet language with numerous results. Among which, there is a program synthesis tool for microcontrollers, especially the EASYdsPIC4 of the Microship dsPIC family.

3.2. Grafcet specification model for the system

From functional specifications of the water supply system described in section 2, we provide the corresponding Grafcet specification model summary described in Figure 2, as shown in Figure 3 and Figure 4. Figure 3 specifies the control of the filling tanks part, considering water sources and energy supply of pumps. While Figure 4 specifies the control of the gates **V2**, **V3** and **V4**.

S0, S15 and S16 are the initial steps. They are activated at the beginning of the process control. When the water level in T_1 is less than the middle level ($!mR1$), the control system makes sure that at least one water source is available $((pE1 + pE2 + pE5) * bR2 + (pE4 + pE5) * bWD + pV1)$ and the appropriate branch of the graph is chosen respecting the priority order of the corresponding water source (SP pump, IP pump and public water V1). The filling process stops if there is no power electricity ($!pE1$ or $!pE2$ or $!pE5$ during the activity of SP; $!pE4$ or $!pE5$ during the activity of IP) or when T_1 is full ($hR1$). The conditions $[S5.T > 20s]$ and $[S9.T > 20s]$ are used to make sure that SP or IP shall continuously operate for at least 20 seconds after each activation.

When there is water in T_1 ($bR1 = true$), the gate V2 is opened. It closes when there is not water in T_1 ($!bR1$). Concerning the gates **V3** and **V4**, they can not be opened both at the same time to convey water from tanks to the lowest three floors; but **V4** is prior to **V3**.

4. Synthesis solution process

Having realized technical design specifications of the water supply system and its grafcet model, let's in this section present the entire architecture of the synthesis process

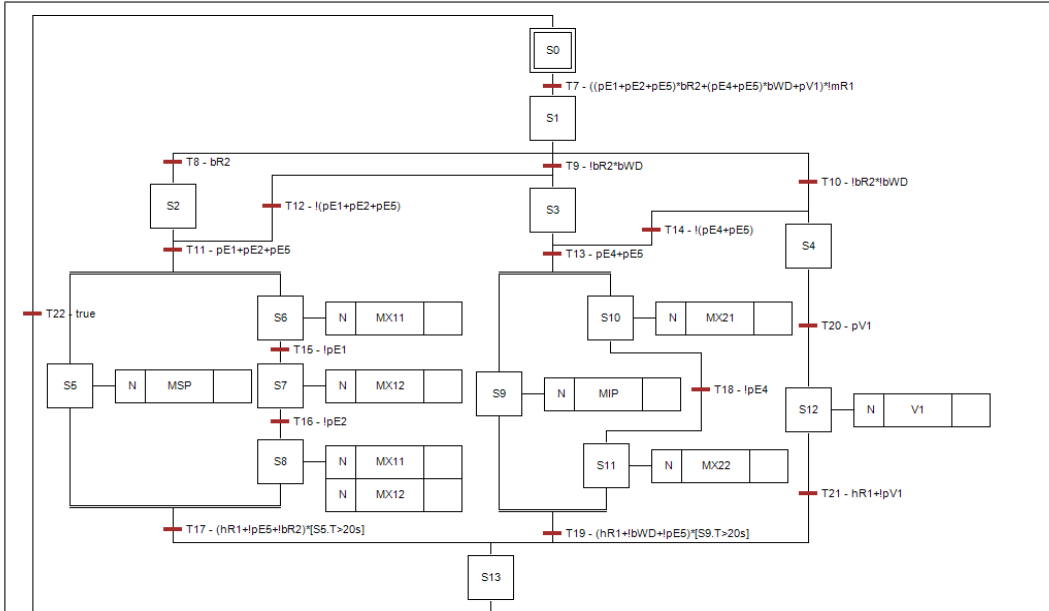


Figure 3. Grafcet specification of tanks-filling sub-system

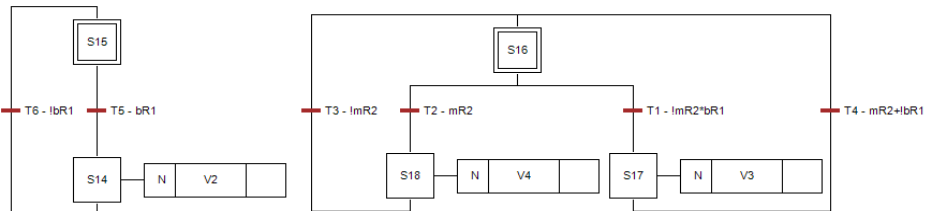


Figure 4. Grafcet specification for gates control sub-system

for any logical control system specified in Grafcet. Referring to Figure 5, the synthesis process can be split into multiple steps which are broadly described as follows:

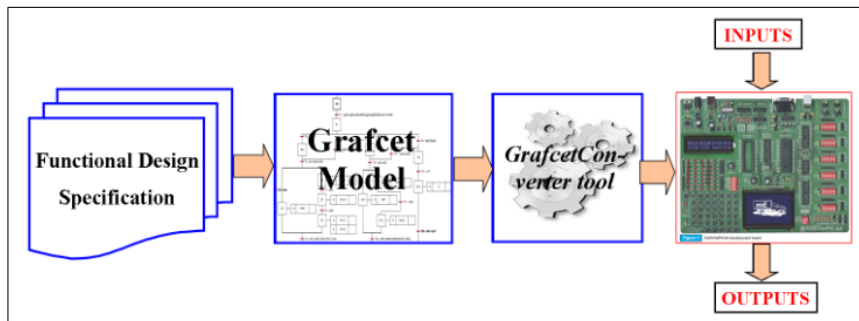


Figure 5. Synthetic approach solution

– **Step 1. Functional Design Specification (FDS) of the system :**

The design and development of any system should start with the description of requirements. An FDS is the most important step in the design of any control system. It provides details of the proposed solution to be implemented, to meet user requirements. Thus, FDS is the documentation that defines what the system should do and what functions and facilities should be provided by this system in order to satisfy the requirements. Through the FDS mentioned in Section 2, we have provided a high-level overview of water & energy supply system (behavior, structure) and we have specified all the functions (e.g. pumping, switching, measuring ...), the objects (sensors, pumps, switches ...), and sequential interactions which are associated with the system.

– **Step 2. Grafcet model :**

The next step is to represent the technical specification of the system by Grafcet model. We propose UniSim software tool in order to edit Grafcet chart [9]. It is a graphical user interface (GUI) that offers gallery of specific graphical objects (shapes) for all Grafcet elements (such as steps, transitions, transition-conditions and actions). The user can easily select these graphical objects, place them onto a drawing page and attach them together in order to create specific grafcet charts. Figures 3 & 4 illustrate the Grafcet model of the case study realized by UniSim editor. Furthermore, UniSim tool permits to reformat Grafcet data into XML format [10], this option ensures that this information can be easily processed by another software application.

– **Step 3. GrafcetConverter tool :**

We have built this software tool in order to directly extract the Grafcet data from XML format file and convert it to a particular set of binary data, which is ready to be transmitted to EEPROM microcontroller memory through serial port. Furthermore, *GrafcetConverter* tool provides a simulation engine with which we can simulate the Grafcet program and verify whether it meets the requirements or not before transmitting it into a microcontroller. Figures 6 & 7 show some interfaces in *GrafcetConverter* tool.

– **Step 4. Integrated Circuit :**

We are using the EASYdsPIC4A microcontroller, a full-feature and very powerful development system for PIC microcontrollers from Microchip [7] that holds a dsPIC30F4013 microprocessor. In C language, we have implemented the Grafcet interpretation algorithm [4] using the MPLAB IDE. The board is programmed by generating a program in assembly language and transferring it to the EEPROM board through USB cable or RS-232 COM port. The microcontroller is then configured and ready to receive binary set of Grafcet data of a system that can be send through the *SerialPortTerminal* interface (Figure 7). Once done and the board reinitialized, the board runs and serves as the sit control of the system.

When a set of data associated to the water supply system is sent to the board, this board serves as the core of the smart control unit. Thus, it receives input signals from the sensors (presence of water, pressure, and electric power), analyzes and generates output signals in form of commands or actions to perform specific acts (open/close gates, turn on/off the pumps or choose a power source). For experimentation, the outputs of the microcontroller can be observed on LEDs while the entries can be enabled using the push buttons.

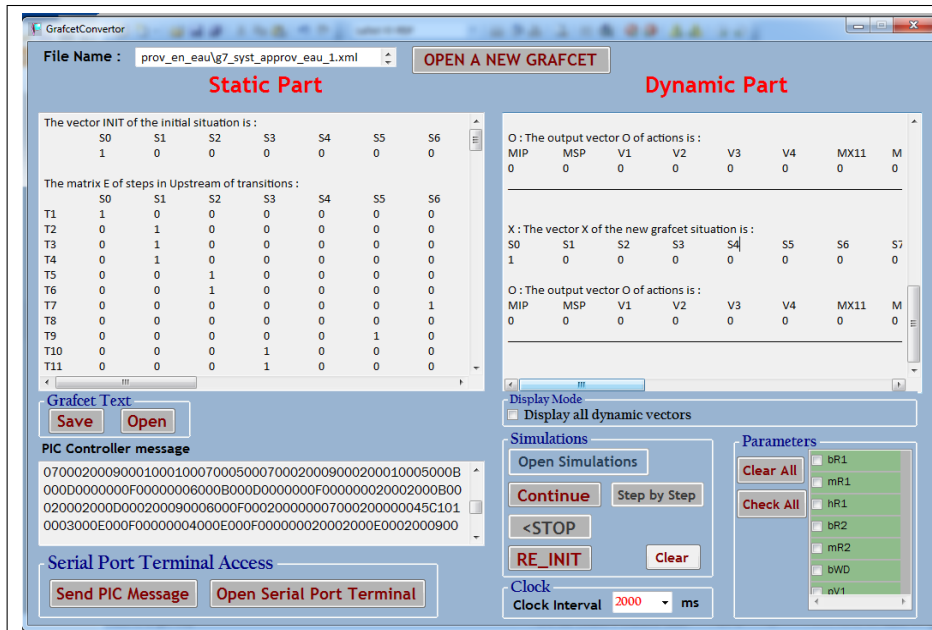


Figure 6. Main GrafcetConverter interface

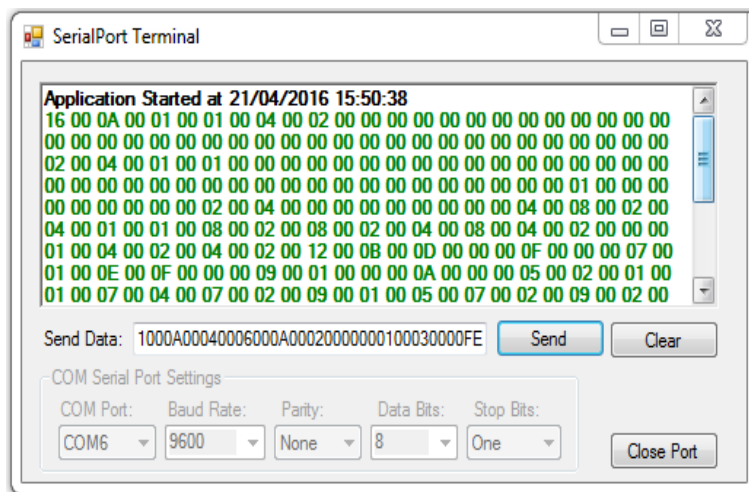


Figure 7. SerialPortTerminal window (to send the board data throught a serial port)

5. Conclusion

In this paper, we have presented the ability to exploit ICT advantages in order to resolve critical issues ongoing in developing countries, particularly water and electrical energy issue. We have designed a sophisticated control system that permits the analysis and the study on the availability of several energy & water sources; and automatically take a decision on the best source to be selected for ensuring continuous water service in the whole building without any interruption and with the lowest cost.

Furthermore, the designed architecture of the water distribution system presents a generic concept of water supply that may be integrated in a building project as well as in an already existing building. This system is realized thanks to the synthesis tool, *GrafcetConverter*, that reads the Grafcet model of the system and converts it to a hexadecimal data set to be transmitted to the selected microcontroller. The current *GrafcetConverter* tool is a version in progress that is actually limited to systems with 16 inputs/outputs and should be upgraded to output code for other interesting microcontrollers.

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