# Intelligent Component Based Batch Control Using IEC61499 and ANSI/ISA S88

D. Ivanova, G. Frey, I. Batchkova

*Abstract*— **This paper proposes an intelligent component based approach for batch control based on ANSI/ISA S88 standard. Common intelligent software components have been built and reused for different application. The components are managed in a control recipe that describes their execution schedule. Furthermore, IEC 61499 standard is adopted as an application framework in which the functional components are implemented as IEC 61499 based function blocks (FB). The operation schedule of the controlled components is then implemented according IEC 61499, based on Scheduler-Selector-Synchronizer ($S^3$) architecture and SIPN models describing the sequence of control execution. An example of the proposed approach based on the real plant for Distillation of Sulphate Turpentine located in Velingrad, Bulgaria is presented and discussed.**

*Index Terms*— **batch control, IEC61499, ANSI/ISA S88, Petri Nets**

## I. Introduction

The global market competition is changing the manufacturing from mass production to mass customization that requires the concept of agile manufacturing. The development of agile manufacturing systems is supported by the rapidly development of Information and Communication Technologies (ICT) and allows the manufacturing of the right products and their distributions at the right places in the right time to the right people. To achieve an agile manufacturing, reconfigurable manufacturing systems are needed and should be developed and used. The key characteristics of reconfigurable manufacturing systems in particular of corresponding control systems are: modularity, integrability, convertibility, customization, reusability and diagnosability. The Component Based Automation (CBA) is a very promising technique supporting these characteristics by the development of next generation intelligent control systems.

Most of the currently used industrial automation control systems are based on traditional control systems or on programmable logic controllers (PLC). In these cases the systems are composed of applications that are difficult to integrate and to expand. On another site the level of intelligence incorporated in manufacturing systems is a dimension hardly accessible by traditional engineering tools and products. This way the most of traditional products and tools are far away from the new challenging technologies of reconfigurable intelligent systems. To overcome these disadvantages of the currently state of the art in the automation and control domain and to follow the last new trends in industrial automation, a new intelligent component based approach for batch control based on ANSI/ISA-S88 and IEC 61499 standards is proposed. The new IEC 61499 based approach is developed and used in order to fulfill the requirements of the Intelligent Manufacturing Systems (IMS) initiative on Mass Customization.

The paper includes 5 sections. In the next section 2 an overview of the applied standards and techniques is done. Section 3 represents the proposed intelligent component based approach and in section 4 a case study based on the plant for Distillation of Sulphate Turpentine is described. Finally some conclusions are done.

## II. Overview of the Applied Standard and Techniques

### A. Overview of the SP88 Batch Control Standard

The ANSI/ISA S88.01 standard is a basic and well accepted standard in the area of batch process industry. It defines the basic terminology and different models facilitating the understanding and the development of batch control systems. The main idea of S88 is to separate the product knowledge from the equipment used. According the standard the batch process is defined as “a process that leads to the production of finite quantities of material by subjecting quantities of inputs materials to an ordered set of processing activities over a finite period of time using one or more pieces of equipment” [1].

S88.01 defines several models describing the equipment, process and procedure hierarchies necessary to make batches as it is shown in Fig.1. The physical model describes the equipment necessary to make a batch and is divided into two organization parts: “Enterprise”, including enterprise, site and area, and “Equipment” composed of process cell, unit, equipment module, control module. Subject of the research proposed in this paper is the “Equipment” part. A process cell contains all of the equipment, including units, required to make batches.

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Dessislava Ivanova is with the Department of Industrial Automation, University of Chemical Technology and Metallurgy, Kl. Ohridski, 8, 1756 Sofia, Bulgaria (telephone: +3592-8163-326, Fax: +3592-8163-326, e-mail: desy_antonova@abv.bg ).

Georg Frey is with the Department of Electrical and Computer Engineering, Erwin-Schrödinger-Str. 12, 67663 Kaiserslautern, Germany (telephone: +49 [0] 631-205-4455, Fax: +49 [0] 631-205-4462, e-mail: frey@eit.uni-kl.de).

Idilia Batchkova is with the Department of Industrial Automation, University of Chemical Technology and Metallurgy, Kl. Ohridski, 8, 1756 Sofia, Bulgaria (telephone: +3592-8163-327, Fax: +3592-8163-327, e-mail: idilia@uctm.edu ).

Batching activities are focused on units, defined as "a collection of process and control equipment, and the associated control logic that carry out one or more major processing activities" [1]. An equipment module according S88.01 standard is "a functional group of equipment that can carry out a finite number of specific minor processing activities". This module can be made up of control modules or other equipment module. In some cases, equipment modules can replace control modules. Control modules are treated as basic elements of the S88.01 physical hierarchy. They are defined as "collections of sensors, actuators, other control modules and associated process equipment that, from the point of view of control, is operated as a single entity" [1]. Examples of control modules may be valves, pumps, PID, PLC, sensors.

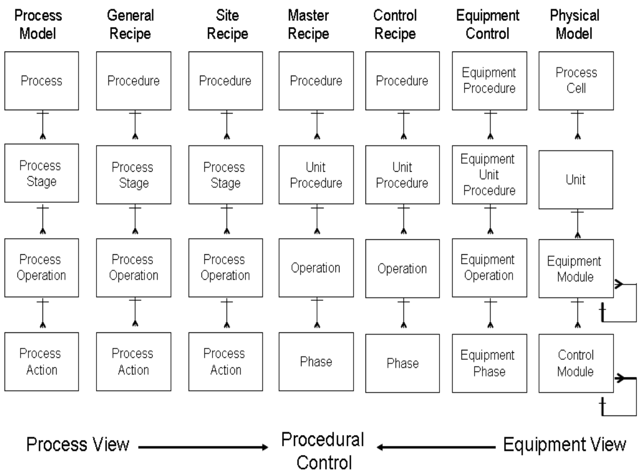


Fig.1. Process and equipment view of S88 Structure [1]

The concept of recipes includes four types of recipes i.e. general, site, master, and control recipes as shown in Fig.1. All recipes are made up of five elements: a header, a formula, the equipment requirements, a procedure, and other information. The procedure as one of the most important elements of the recipe defines the procedural logic that must be followed to make a desired product. The procedural models have hierarchical organization that allows the reuse of recipe elements and facilitates and simplifies the recipe development. S88.01 Batch Control Standard is the way to the modular approach to the automatic and manual batch process. The standard structure gives abilities for clearly definition of processes and product requirements.

This paper covers mainly the development of control recipes and procedural control. The control recipes contain the necessary information for the batch processes. Signal Interpreted Petri Nets (SIPN) are used to describe the control recipes. They provide more details for analysis and verification in a formal way. The IEC 61499 based methodology is used to implement the control scenario. They will be shortly presented in the next paragraphs.

### *B. Overview of the IEC 61499 Standard*

IEC 61499 Standard defines the basic concepts and a methodology for design of distributed process measurement and control systems. It is based on the function block as a main building block of an application. The function block may be used in the design of re-usable intelligent software components and even more through the suggested standardized methodology to be used in the development of complex distributed control systems. The Function block concept is defined by Lewis as "an abstraction mechanism that allows industrial algorithms to be encapsulated in a form that can be readily understood and applied by industrial engineers, who are not specialists in the implementation of complex algorithms" [2]. The component model proposed in IEC 61499 Standard, based on the basic function block concept is shown in Fig.2.

The basic function block is presented by an input and an output interface composed of input and output events and data (Fig.2.a). The internal view of a basic function block includes an Execution Control Chart (ECC), internal data and internal algorithms. The ECC is a state machine used to control the execution of algorithms associated to the function block. A function block is characterized by its type name and instance name, which are used to identify a function block. The event and data inputs and outputs are required for the interconnection of different function blocks to function block systems, while the ECC, internal data and internal algorithm describe the internal behaviour of the function block. The kernel of the function block is its Execution Control Chart (Fig.2.b).

An ECC consist of states, transitions and actions, which invokes the execution of the algorithms, which are associated to the ECC states, in response to event inputs. One of the states is initial state and the other execution control states may have one or more execution control actions associated. Each execution control action may have one algorithm or one output event associated. The evolution of the ECC state machine from an execution control state to other is enabled by the execution of transitions. In general, the ECC is the relationship between events and algorithm executions, which are specified by the special kind of even-driven state machines. The architecture of basic function block and corresponding ECC specify the relationship between control hardware and software. The whole engineering process proposed by IEC 61499 Standard is improved in terms of reliability, reusability and interoperability.

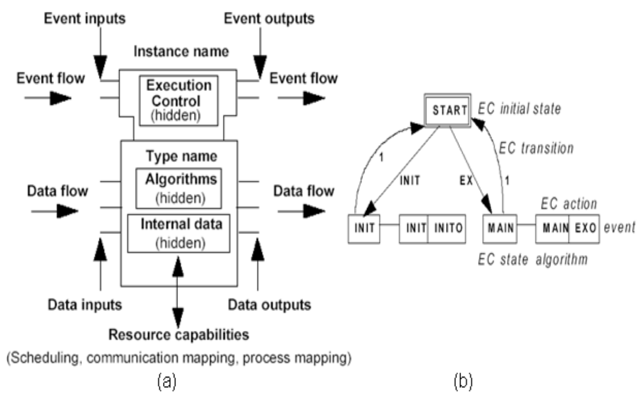


Fig.2. (a) Basic FB and (b) ECC

### *C. Signal Interpreted Petri Nets*

SIPNs are an extension of ordinary place/transition nets with input and output elements. Graphically, they have two basic types of nodes, i.e. places and transitions, connected through directed arcs. The places are associated with output signals, and the transitions are labeled by Boolean expressions of input signals, which serve as firing conditions. A hierarchical timed SIPN (htSIPN) as in [4] - [5] is described by a 12-tuple: SIPN = $(P, T, F, m_0, I, O, \varphi, \omega, \Omega, \nu, \eta, \tau)$.

- $(P, T, F, m_0)$ is an ordinary Petri net with places P, transitions T, arcs F, and binary initial marking $m_0$, with $|P|, |T|, |F| > 0$;
- I is a set of input signals with $|I| > 0$;
- O is a set of output signals with $I \cap O = \emptyset$, $|O| > 0$;
- $\varphi$ is a mapping associating every transition $t_i \in T$ with a firing condition $\varphi(t_i)$ = Boolean function in I;
- $\omega$ is a mapping associating every place $p_i \in P$ with an output $\omega(p_i)$. The output is assigned as an interval over the corresponding domain of the output signal. This interval definition includes as special cases an unspecified output (do not care) and the specification of a single value.
- $\Omega$ is an output function which combines the output $\omega$ of all marked places.
- $\nu$ is a variable definition, which assigns a numeric data type according to IEC61131 (e.g. BOOL, INT, REAL) to every signal $s \in I \cup O$.
- $\eta$ is a mapping associating places $p_i \in P$ with subnets $\eta(p_i)$, $\eta$ is not defined ($\eta(p_i)$ = nil) for places containing no subnet.
- $\tau$, associating every arc $f_i$ that is an input arc to a transition (i.e. $f_i \in (P \times T) \cap F$ ) with a time delay $\tau_i$.

The dynamic behaviour of an SIPN is given by the flow of tokens through the net i.e. the change of its marking. This flow is enabled by the transitions firing. A transition fires immediately if its pre-places are marked (in the case of timed arcs at least for the defined time delay), its post-places are unmarked, and its firing condition is true. The firing of a transition $t_i$ removes a token from each of its pre-places and puts a token on each of its post-places.

## III. Description Of The Proposed Approach

The proposed approach for intelligent component based batch control is connected to the development of common functional components and is illustrated in Fig.3. It is a combination of well-known approaches based on the ANSI/ISA S88.01 [1], IEC 61499 [2] - [3] and SIPN [4] - [5]. SIPNs are used to model the master and control procedures, which are mapped into IEC 61499 applications. The sequence of component execution is represented in the SIPN model and then is used as a control scenario for the FB-based system. In order to achieve reusability and an intelligent behavior of the designed components, a task scheduling concept containing Scheduler, Selector and Synchronizer ($S^3$) [6] has been applied. $S^3$ deals with re-configurability at the control execution stage of the controlled component [9]. The main goal is to provide high reusable intelligent components concerning batch control process and an easy way to reconfigure on-line by their executions. As a result, the intelligent control strategy can be more flexible.

Related works which combine the use of S88.01 and IEC 61499 standard can be seen in [7] - [8]. Their approach adopts Procedural Function Chart (PFC) according to S88.01 to describe the batch operation. The information on each operation was signal-based. One to one mapping from PFC into the IEC 61499 FBs' network is done afterward. The proposed approach is based on a mapping between PFC and SIPN that is explained and discussed in [10]. The SIPN model is implemented in IEC 61499 based components using the following main rules:

- Place's inscription denotes the related functional component implemented as one or more FBs either basic (e.g. valve, pump, etc.) or composite.
- Token flow of SIPN denotes the sequence of functional components' execution or the control sequence in FBs' network.
- Transition's inscription denotes conditions (i.e. input variable) which are required to move from one component to the others.
- Time delay is drawn at the arc and implemented as a FB.

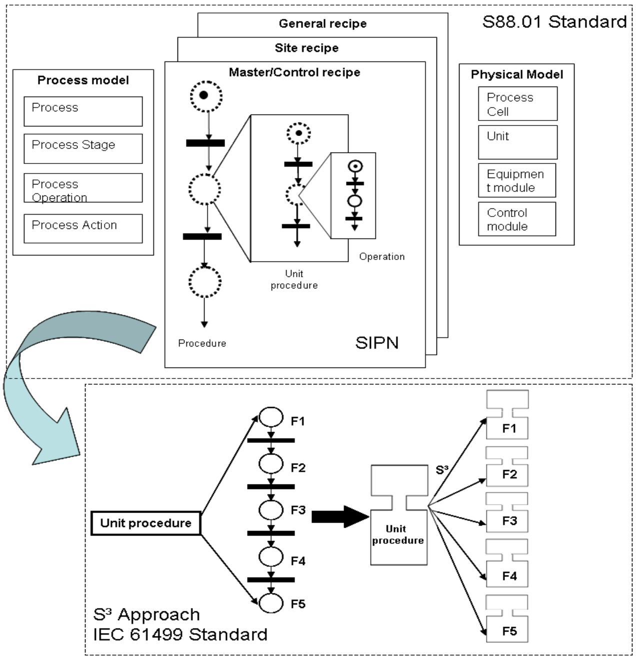


Fig.3. Map of the suggested approach

Furthermore, SIPN which describes Procedure, Unit Procedure and Operation are hierarchical elements and can be mapped out in hierarchical IEC 61499 composite function blocks. By using this approach, once the intelligent components are built and the reuse for different application purposes can be done properly. Through the creation of intelligent reusable control components, a lot of engineering time and human recourses may be saved and new characteristics of the developed automation and control system such as flexibility, re-configurability, portability and agility may be achieved.

## IV. Case Study

### A. Technological Description

The proposed approach is illustrated with an example of the real plant for Distillation of Sulphate Turpentine located in Velingrad, Bulgaria. Fig.4 depicts the P&ID of the plant.

The process starts with pumping a batch of liquid feed into the batch tank B-01. When the tank is about 80% full, the feed is stopped and the content of the batch tank is heated to boiling by the preheated steam in the reboiler W-01. Once the mixture starts to boil, the vapour is carried up the packed column K-01 and is condensed in the overhead condenser – W-02. Vapour rising through a column above the tank combines with the reflux coming down the column to effect concentration. The condensate flows either to a reflux drum or to a decanter. Reflux is then pumped back to the top of the column. At start up, the system is operated at total reflux until the required purity of the most volatile component is achieved. At this point, the product is withdrawn at a rate controlled by the reflux ratio. The reflux ratio is set according to data from an on-line analyzer or temperature profile in the column. When the reflux ratio becomes too high (typically 15 or 30 to 1), then it is no longer economical to continue to produce a top product. The flow is diverted to slop out tank, and the reflux ratio is reduced. Eventually the most volatile component will be completely driven off. The steps can be repeated for each volatile component required recovering.

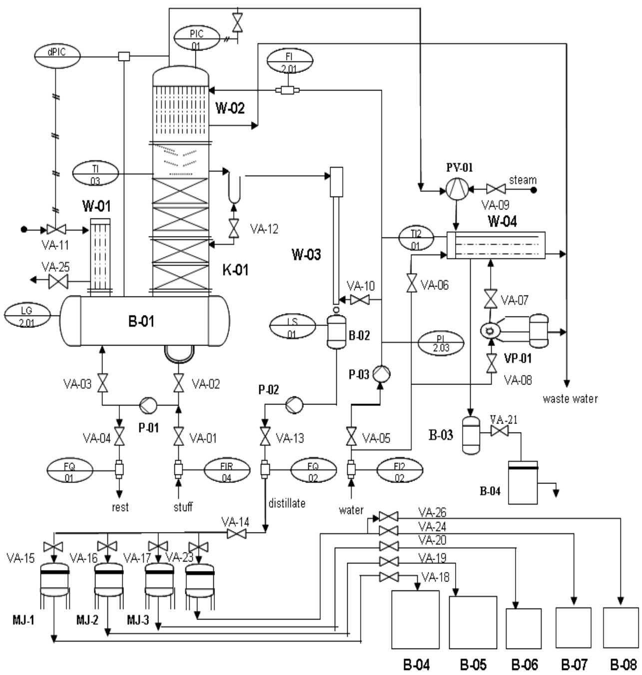


Fig.4. P&ID of the plant for distillation of Sulphate Turpentine

Currently all discrete control activities are manually done by two operators. This way, the defined three operating phases have the following continuances: 2.83 hours for the start-up, 36 hours for the separation and 8 hours for the shutdown. The process requires considerable operator intervention and the development of an automatic discrete control system is expected to: shorten the batches, improve the quality of products and increase the system reliability.

*B. Description of unit procedures*

The subject of the research presented in this paper is the “Turpentine Production” cell caring out a batch distillation process, which consists of three process stages: Start up, Rectification and Shut Down. To perform the major process activities in the process cell, several unit procedures are defined: “Mixture Charging”, “Vacuum Creation”, “Water Circulation”, “Steam Heating”, “Rectification”, and “Discharging”. These unit procedures are executed by functional components such as valves and pumps along with some analogue indicators. The reuse of intelligent software components depends on the functional requirements to the units. At a procedure level, these unit procedures will be run in series for the batch process: <”Mixture Charging”, “Vacuum Creation”, “Water Circulation”, “Steam Heating”, “Rectification”, and “Discharging”>. After the batch is finished, a new batch can be processed.

The plant is started by the operations of unit procedure “Mixture Charging”. It consists of five operations. Each operation has some phases, which are the lowest level in the procedural control recipe describing process of specific tasks or functions. Operation 1 is to open the valves VA-01 (1), VA-03 (1) and turn on the pump P-01 (1) when some conditions are reached (pressure PI05 = 6 bar & flow FIR04 = 1). Operation 2 is to close valve VA-01 (0) if LG2.01 (B-01 = 10000 l) is true. Operation 3 is to open valve VA-02 (1) if PIC-01 is 260 mbar. Operation 4 is to open valve VA-04 (1) and close valve VA-03 (0) if PI2.03 = 0 mbar is true. Operation 5 is to close valves VA-02 (0), VA-04 (0) and turn off the pump P-01 (0) if PI2.01 = 0 & FQ01 = 0 are true.

The second unit procedure - “Vacuum Creation” is responsible to open the valves VA-06 (1), VA-07 (1), VA-09 (1) and turn on the pumps PV-01 (1) and VP-01 (1), included in the first operation. The second operation is to open the valve VA-08 (1) and to switch PIC01 in “automatic mode” if PI2.04 = 280 mbar. The operation 3 is to switch dPIC01 in “automatic mode” when dPIC-01= 25 mbar. The operation 4 is to switch dPIC-01 in “manual mode” if LS2.01 = Lmin (300 l) is true. The operation 5 is to turn off the pumps VP-01 (0), PV-01 (0) and to switch PIC01 in “manual mode”. The operation 6 is to close the valves VA-06 (0), VA-07 (0) and VA-08 (0). The last operation 7 is to close the valve VA-09 (0) if PI2.03 = 0 mbar.

The third unit procedure – “Water Circulation” is responsible to open the valves VA-05 (1) and VA-10 (1) for water circulation. Operation 2 is connection to turn on the pump P-03 (1) if PI2.03 > 0 and FI2.02 ≥ 300 m³/h. The operation 3 is to close the valves VA-10 (0) and VA-05 (0) if PIC1.01 = 0. The last operation in this unit includes only one phase, connecting to turn off the pump P-03 (0) if TI03 = 90ºC.

The next unit procedure – “Steam Heating” consists of tree operations, the first one is to open the valve VA-11 (1) and to close the VA-25 (0) if PIC-01 = 260 mbar. The second one is connected with closing the valve VA-11 (0) and opening VA-25 (1). The last operation is only to close the valve VA-25 (0) if TI01=90ºC.

The last two unit procedures represent the rectification process in a plant. “Rectification” is based on achieving the temperature profile in the column. The different operations are connected to the different fractions, drawn during one batch cycle. The operations in unit “Rectification” could be summarized as follow:

T1min = 108ºC || T1max = 108ºC || T2min = 106.6ºC || T2max = 106.6ºC || T3min = 107ºC || T3max = 107ºC || T4min = 21ºC || T4max = 25ºC || FI2.01 = 40 || Timer1 = ON || R (1)

IF Time = 1 h THEN T1min = 108ºC || T1max = 120ºC || T2min = 106.6ºC || T2max = 119ºC || T3min = 107ºC || T3max = 107ºC || T4min = 21ºC || T4max = 25ºC || FI2.01 = 40; Timer1 (6 h) = ON || R(1, 60/10)

T1min = 120ºC || T1max = 120ºC || T2min = 119ºC || T2max = 119ºC || T3min = 107ºC, T3max = 107ºC || T4min = 21ºC || T4max = 25ºC || FI2.01 = 40 || Timer1 (5 h) = ON || R (1, 100/10)

T1min = 120ºC || T1max = 124.7ºC || T2min = 119.8ºC || T2max = 122.1ºC || T3min = 108.3ºC || T3max = 115ºC || T4min = 21ºC || T4max = 25ºC || FI2.01 = 40 || Timer1 (3 h) = ON; R (1, 120/10)

T1min = 125ºC, T1max = 127ºC; T2min = 122.1ºC, T2max = 122.6ºC; T3min = 115ºC, T3max = 120.4ºC, T4min = 21ºC, T4max = 25ºC, FI2.01 = 40; Timer1 (2 h) = ON; R (1, 160/10)

T1min = 127ºC || T1max = 133.5ºC || T2min = 122.6ºC || T2max = 122.8ºC || T3min = 120.4ºC || T3max = 120.7ºC || T4min = 21ºC || T4max = 25ºC || FI2.01 = 40 || Timer1 (1 h) = ON; R (1, 160/10)

Where the T1 is the temperature in tank B-01; T2, T3 and T4 are the temperatures through the length of the column. FI2.01 is the amount of the cooling water needed to effect the condensation. The Reflux Ratio for the different fractions is named R. At the beginning the system works in total reflux mode, the first fraction continued six hours and the material is alfa-pinene, the second fraction continued five hours and product is beta-pinene, the next two fraction are middle fractions. They are mixture of alpha-pinene and beta-pinene. The last fraction continued one hour and the product is delta -3 carene.

The last unit procedure - "Discharging" is responsible to open the route to the product tanks for discharging the desired fractions. This unit procedure could be separated into ten operations to achieve the discharging process. The defined operations are:

1. VA-13 (1) || VA-14 (1) || VA-15 (1) || P-02 (1) – every 7s; IF LS 03 (≥ 0.2 $m^3$) = TRUE THEN VA-18 (1) ELSE (LS 03 = FALSE) VA-18 (0)
2. IF LS 01 (= 0) = FALSE THEN P-02 (0) || VA-15 (0)
3. VA-16 (1) || P-02 (1) – every 7s; If LS 04 (≥ 0.2 $m^3$) = TRUE THEN VA-19 (1) ELSE (LS 04 = 0 ) = FALSE VA-19 (0)
4. IF LS 01 = 0 = FALSE THEN P-02 (0) || VA-16 (0)
5. VA-17 (1) || P-02 (1) – every 7s; IF LS 05 (≥ 0.2 $m^3$) = TRUE THEN VA-20 (1) ELSE (LS 05 = 0 = FALSE) VA-20 (0)
6. IF LS 01 = 0 = FALSE THEN P-02 (0) || VA-17 (0)
7. VA-23 (1) || P-02 (1) – every 7s || VA-24 (1)
8. IF LS 01 = 0 = FALSE THEN P-02 (0) || VA-23 (0) || VA-24 (0)
9. VA-23 (1) || P-02 (1) – every 7s || VA-26 (1)
10. IF LS 01 = 0 = FALSE THEN P-02 (0) || VA-23 (0) || VA-26 (0)

The "Mixture Charging" unit is modeled by five places and four transitions associated with input signals. The evaluation step by step is realized by the flow of token from one component to the other, i.e. the move of its marking. The SIPN model of the "Mixture Charging" unit is created using the SIPN Editor [5] and is shown in Fig.5.

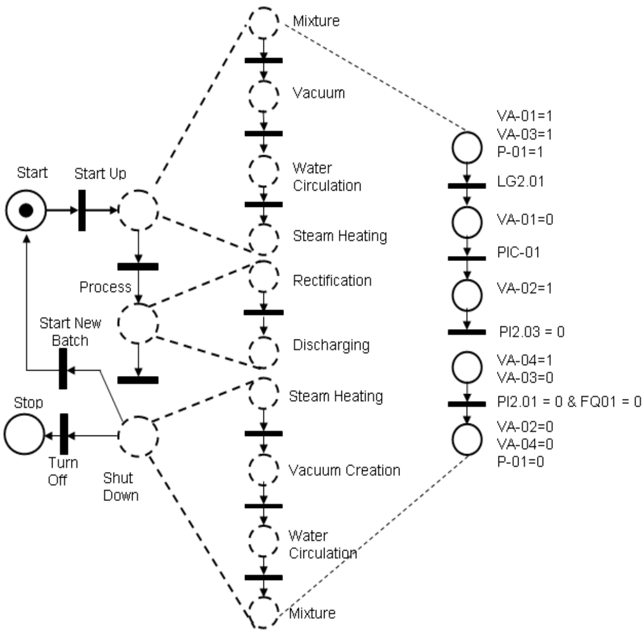


Fig.5. SIPN models of the "Mixture Charging" unit procedure

### *C. IEC 61499 Implementation for "Mixture Charging"*

For "Mixture Charging" unit five generic components (valves VA-01, VA-02, VA-03, VA-04 and pump P-01) are used. Those components compose the common functional component namely valve and pump.

The structure of "Mixture Charging" unit is hierarchical and can be mapped into IEC 61499 composite intelligent function blocks. Token flow denotes the sequence of functional components' execution and can be modeled as events flow among FBs' network concerning the control flow. Besides, inputs and outputs are variable of the FBs.

To deal with re-configurability of the functional components at the execution stage, $S^3$ technique is applied. It consists of three main components, i.e. Scheduler, Selector and Synchronizer. The scheduler gets the predefined task schedules of the execution and computes it to be sent to the Selector step by step. The task schedules considered here are based on the SIPN model describing the unit processes. Thus, the selector will run the regarded functional components - which are as controlled objects – according to the given step. The executed task will be resumed by the Synchronizer. A confirmation will be send to the Scheduler once the required task has been done and a new task from Scheduler is required afterward.

The implementation of the unit process according to the proposed approach is shown in Fig.6. As a start point, SIPN task schedule for unit operation attached in Fig.6 is migrated to the function block. $S^3$ technique is applied with corresponding FBs (Scheduler, Selector, and Synchronizer) and logic execution explained above. For the definition of the sequence of the operation, Schedule of operation (SOP) can be used:

SOP_Startup mixture charging = <F1 || F3 || F5, F1, F2> = <21, 1, 2>

SOP_Shutdown mixture charging = <F1 || F4, F2 || F4 ||

F5> =<12, 26>

The reusability values of the functional components operations are F1= $2^0$, F2 =$2^1$, F3=$2^2$, F4=$2^3$, F5=$2^4$.

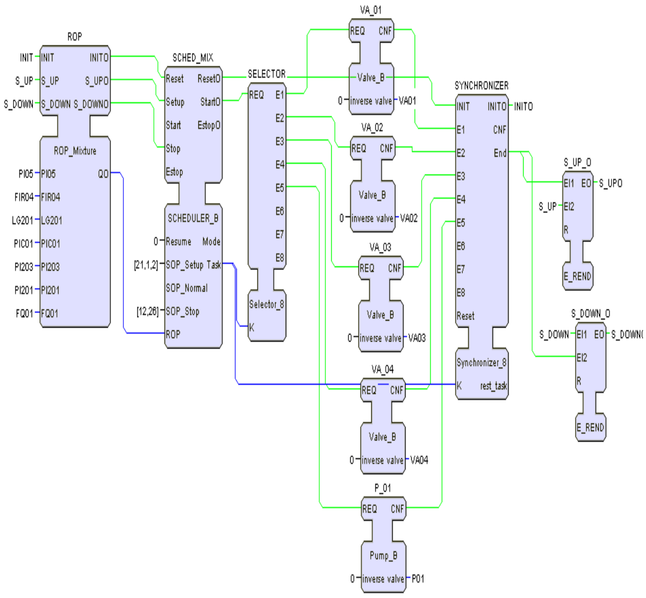


Fig.6. FBs' network of "Mixture Charging"

In each sequence, the functional components with the corresponding device are arranged in an ordered list separated by commas and enclosed by corner brackets.

Furthermore, all units in the plant for Distillation of Sulphate Turpentine are managed at the procedure level in a series order as the most cases in batch control. The series order is quite simple and reduces the complexity in managing the unit procedure. Fig.7 illustrates the control of the six unit procedures using S³ architecture. Each unit is represented by an intelligent FB, i.e. "Mixture Charging", "Vacuum Creation", "Water Circulation", "Steam Heating", "Rectification", and "Discharging". FBs Scheduler, Selector, and Synchronizer are used to control those units using S³ approach. Their SOP for normal operation based on the name of the controlled FBs is as follows:

$SOP_{normal}$ = ⟨Mixture Charging, Vacuum Creation, Water Circulation, Steam Heating, Rectification, Discharging, Steam Heating, Vacuum Creation, Water Circulation, Mixture Charging⟩

SOP_normal_installation =
<1,1,1,4,4,4,16,16,64,256,256,512,512,256,512,512,256,512,512,256,512,512,256,512,512,512,256,128,128,8,8,8,8,32,32,2,2 >

## V. Conclusions

This paper presents a combination of SIPN concept and recipe methodology of ANSI/ISA S88 implemented in IEC 61499 Standard by S³ mechanism. The proposed approach traces the migration path to IEC 61499 based control application. This scenario is influenced by some properties in Batch Control Systems as flexibility, interoperability achieved by using generic functional re-usable control components splitting and joining to different system objects. Our goal is to provide high reusable components concerning batch process and an easy way to reconfigure their executions. The suggested intelligent approach based on unification of these three methodologies provides high reusability of the components with the similar functions. As a result the engineering time and development cycle can be reduced that is cost effective.

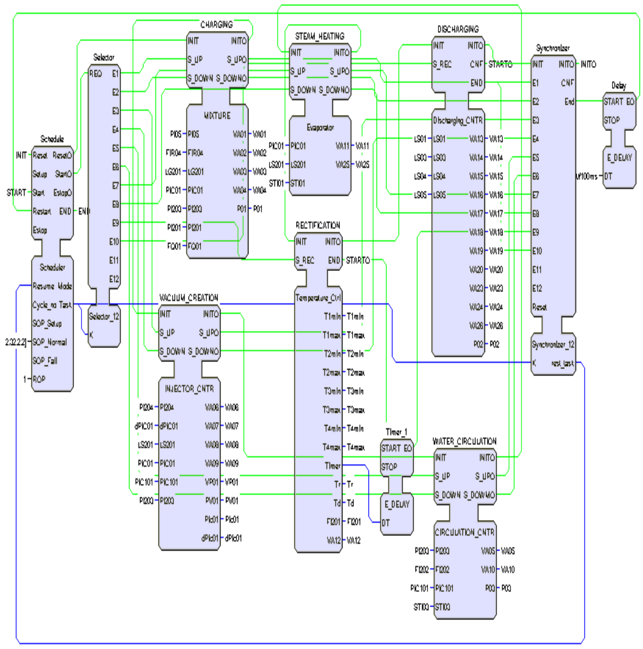


Fig.7. FBs' network of Installation for Distillation of Sulphate Turpentine

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