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Using Hierarchical Coloured Petri Net to Support Substation Restoration

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***Abstract*—In this work, a solution to restore a substation is proposed, using hierarchical coloured petri net, in a safe, reliable, fast and efficient way. This solution intends to solve the limitations of the solutions already presented in the academic world to solve this problem. A real substation case is considered. Using formal methods, a formulation and solution to this problem through structured, scalable and compact mathematical representations are possible. Algorithms and proprieties of the used formalism let analysis formally.**

***Index Terms*—Automation, Formal languages, Petri nets, Power system modeling, Power system restoration, Power transmission control, Substations.**

I. Introduction

Transmission lines transmit a large volume of energy, very often, for a long distance. The transmission system consists of high voltage lines of transmission - from 69 to 750 Kilovolts (kV) - connected in a network. In the route between generators and cities, the electricity goes for several substations, where transformers increase or decrease its voltage.

A substation connects all the power system, letting energy flows, and must operate, during all the time, in its nominal conditions, i.e., supplying all the loads that it was projected to. However, blackouts of substation, random events, although they are not wished, occur very often. Considering operational data of the Hydroelectric Company of San Francisco (CHESF), a Brazilian government company which generates and transmits electrical energy, in 2005, from January to April, the ten biggest occurrences of substation blackouts became 1.075,768 Megawatts-hour (MWh) unavailable with mean time duration of 30 minutes for each one of them. The financial costs associated to MWh depend on the commercial contracts.

When these blackouts occur, there are social and economic consequences. The social consequences are due to the supply interruption of the electrical energy to the society: homes, schools, hospitals, industries, etc. The economic consequences, in Brazil, are due to the National Operator of the System (ONS) charging. The ONS, responsible for the coordination and operational control of the electrical energy generation and transmission plants in National Interlinked System (SIN), under National Agency of Electrical Energy (ANEEL) supervision and regulation, charges through the variable item. This charging for non-programmed blackouts represents a fine up to one hundred times more than revenue value per minute in case of electrical energy flow unavailability by the transmitter, i.e., the transmitter, besides not earning the revenue value for supplying electrical energy, has to pay a fine up to one hundred times more than value which would be revenued, if it had not interrupted electrical energy flow. In this scenario of social and economic consequences, in case of a substation blackout, it is important the restoration of the services, in a safe and reliable way, as soon as possible.

After a blackout, the task of restoring a substation is complex, stressful and indispensable to the plant operators. Currently, in CHESF, the operators accomplish this task manually, according to the operational procedures which state procedures to be accomplished to the restoration. During the execution of these procedures, there are risks of command errors due to the fact the operators, in a general way, do not operate electrical system under these conditions. Therefore, the development of a system which supports the operator to restore a substation constitutes a relevant problem. This system aims to offer: reduction of the needed time to accomplish plant commands, reducing time of energy flow unavailability; improvement of internal processes and service quality accomplished for the electrical energy companies; increase of electrical energy companies profits, through higher availability of energy flow, avoiding also some fines for service unavailability to the customers.

In last years, several researches have been accomplished with power system restoration [1], [2]. Associated with mechanisms of inference, several techniques of expert systems based on the knowledge [3], [4], multi-agent systems [5], [6] and solutions with heuristic researches [1], [2], [7], [8] associated with specific programming methods have been proposed to guide operators, when these ones need to restore a substation. However, some of the limitations of these solutions are the difficulty of representing a knowledge base and/or developing an efficient inference mechanism to determine which actions have to be taken, from a large volume of knowledge based on rules; bad performance, working with multiple faults; high dependence of operator knowledge which compromises knowledge acquisition and solution performance.

The use of Petri nets (Pns) to solve problems related to applications in power systems [9] has received a large attention. A system of a knowledge representation, through Pn, was proposed to accomplish the restoration of a substation automatically [10]. However, this solution has some limitations, such as: dependency of the operator knowledge which compromises knowledge acquisition and solution performance; is not robust, i.e., if a problem to acquire information or command equipment occurs, a series of incorrect commands can happen, which can cause severe damages to the power system; is not structured and systematized which causes a lack of generalization capacity for this one; in real cases, several hundreds of states will be needed to the representation of this system in Pn, leading to a complex system which makes the maintenance and/or ampliation of this system difficult; there is no prove, e.g., through formal methods, of the correctness of this solution, making possible deadlocks, livelocks or incorrect actions; operational datas of the equipments are not considered, making possible incorrect behavior of this solution; in a real case, a possibility of integration for this solution is not discussed; the problem related to acquisition time and processing time of the information to take decisions which can cause an incorrect behavior of this solution is also not discussed.

With the advent of the digital systems technology of Measurement, Protection, Command, Control, Supervision and Regulation (MPCCSR) to substations, which has industrial computers and digital relays, supported by high speed and availability networks of optical fibers, performing these functions, the dynamic of the substation can be considered as discrete. Currently, there is not a safe, reliable, efficient, methodological and scalable computational method which solves in a satisfactory way the problem of restoring power system. However, in this current technological scenario, a computational system to support the operator during the execution of the operational procedures for restoring a substation automatically, after a blackout, is relevant.

Although there are some limitations on the proposed solution in [10], modeling of critical Discrete Event Systems (DESs) through Pn is promising because the behavior of these systems can be represented in a very detailed way and through formal methods. Therefore, the use of algorithms and proprieties of this formalism to formal analysis of these systems is possible. In this work, a study and an implementation of a solution through Hierarchical Coloured Petri Net (HCPN) to formulate and solve the problem to restore a substation are proposed as follows.

- Logical modeling with HCPN to formulate the problem of restoring a substation;
- Study of the theory for projecting controllers to Pn;
- Implementation of the controllers to solve the problem of restoring a substation.

Therefore, this work is organized as follows. In Section II, introductory basic principles of HCPN is described. In Section III, the problem to restore a substation and techniques of restoration are considered. In Section IV, analysis is explained. In Section V, conclusion is presented.

II. Basic Principles of Hierarchical Coloured Petri Net

Coloured Petri Net (CPN) is a formal method with graphical representation to specify concurrent systems. Events are associated with transitions. In order for a transition to occur, several conditions may have to be satisfied. Information related to these conditions is contained in places. Some such places are viewed as the ”input” to a transition; they are associated with the conditions required for this transition to occur. Other places are viewed as the output of a transition; they are associated with conditions that are affected by the occurrence of this transition. Transitions, places, and certain relationships between them define the basic components of a CPN. A CPN has two types of nodes, places and transitions, and arcs connecting these ones. It is a bipartite graph in the sense that arcs cannot directly connect nodes of the same type; rather, arcs connect place nodes to transition nodes and transition nodes to place nodes.

Using CPN modeling, similar systems can be represented on the same net, being only needed to use ”tokens colours” to represent each type of a specific system. For a given place all tokens must have token colours that belong to a specified type. This type is called the colour set of the place. Colour sets determine the possible values of tokens, analogously, to the way in which types determine the possible values of variables and expressions. For historical reasons, values and types are called by colours and colour sets respectively. ”Coloured tokens” can be distinguished from each other. With this modeling is possible to build a big CPN from smaller CPNs. From declarations, it can be seen what the colour sets are. The declarations use a language called CPN ML [11]. This language is used by CPN Tools [1].

A distribution of tokens on the places is called marking. The initial marking is determined by evaluating the initialization expressions. The marking of each place is a multi-set over the colour set attached to the place. Multi-sets are needed to allow two or more tokens to have identical token colours. In CPN, the current marking of a given place is represented by a small circle with an integer indicating how many tokens there are and a text string next to the circle with a multi-set showing what the individual token colours are, and which coefficients they have. By convention, the circle and the text string for places which have no tokens are omitted.

Allowing more complex markers also means that the moves in the ”Petri Net game” become more complex. The token colours can be inspected by the transitions, which means that the enabling of a transition may depend upon the colours of its input tokens. It also means that the colours of the input tokens may determine the colours of the output tokens produced, i.e., the effect of the transition. To describe this more complex

[1] More information about CPN Tools can be obtained in http://wiki.daimi.au.dk/cpntools/cpntools.wiki

situation, more elaborate arc expressions are needed. It is no longer sufficient to have an integer specifying the number of tokens which are added/removed. Instead arc expressions which specify a collection of tokens - each with a well defined token colour - are needed. To do this, arc expressions which evaluate to multi-sets are used. In Figure 1, a representation of the basic graphical elements of a CPN and their characteristics is shown.

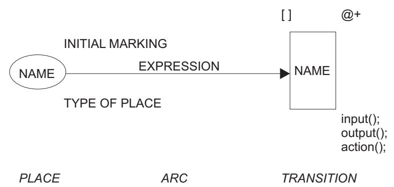

Fig. 1. Basic Elements of a Coloured Petri Net.

When a transition is enabled for a certain binding it may occur, and it then removes tokens from its input places and adds tokens and the colours of these tokens are determined by the value of the corresponding arc expressions evaluated with respect to the binding in question. A pair t,b where t is a transition and b a binding element for t is called a binding element. The guard is a boolean expression, i.e., an expression which evaluates to either true or false and it may have variables in exactly the same way that the arc expressions have. The purpose of the guard is to define an additional constraint which must be fulfilled before the transition is enabled. Two transitions in a CPN can be concurrently enabled if there exist bindings for the variables in the guard and the surrounding arc expressions, such that the transitions use disjoint set of tokens. A CPN consists of three different parts: the net structure, i.e., places, transitions, arcs, declarations and net inscriptions, i.e., the various text strings which are attached to the elements of the net structure.

CPNs can have several another types of descriptions, e.g., hierarchical. It is possible to construct a large CPN by combining a number of smaller nets with HCPNs. HCPNs have been developed to make possible to relate a number of individual CPNs to each other in a formal way, i.e. in a way which has a well-defined semantics and therefore allows formal analysis. Each HCPN can be translated into a behaviorally equivalent non-hierarchical CPN, and vice versa. The basic concepts and the analysis methods of non-hierarchical nets can be generalized to HCPNs. The two hierarchy constructs are known as substitution transitions and fusion places. They allow to build a large hierarchical CPN by composing a number of smaller non-hierarchical CPNs. The intuitive idea behind substitution transitions is to allow to relate a transition and its surrounding arcs to a more complex CPN - which usually gives a more precise and detailed description of the activity represented by the substitution transition. A set of non-hierarchical CPNs is called page. Subpage is the page which contains the detailed description of the activity modeled by the corresponding substitution transition. Each substitution transition is said to be a supernode of the corresponding subpage while the page of a substitution transition is a superpage of the corresponding subpage. In a HCPN with several page instances, each of the page instances will have its own private marking, which is independent of the markings of the other instances in a similar way that each procedure call has its own private copies of the local variables in the procedure. The intuitive idea behind fusion of places is to allow to specify that a set of places are considered to be identical, i.e., they all represent a single conceptual place even though they are drawn as individual places. This means that when a token is added/removed at all the others. More information about CPN and HCPN can be obtained in [12], [13].

There is no control theory for DES modeled by CPNs. There is a large body of results on the control of CPNs when the control paradigm is changed from ”language viewpoint” of supervisory control theory to a ”state viewpoint” for a given uncontrolled system modeled by a CPN. The specifications on the uncontrolled system are stated in terms of forbidden states and the control mechanism is to decide which of the controllable and enabled transitions in the system should be allowed to fire by the ”controller”. The controller should guarantee that none of the forbidden states is reached, and should do so with ”minimal intervention” on the behavior of the system. The synthesis of such a controller should exploit the system structure captured by the CPN model. Information about formal analysis, dynamic and static proprieties of CPN can be obtained in [12], [13].

III. Techniques of Restoration

The comprehension of the proposed solution in this work is important. In Figure 2, a block diagram of the proposed solution is shown. The proposed solution interacts with the supervisory system. Substation information is received through the boolean logical functions of restoration. Substation commands are sent, aiming to the substation automatic restoration. Supervisory system receives substation information through event and analog points supervision and sends substation commands. In this solution, when enabled transitions fire, information from supervisory system is obtained, aiming to take decisions to achieve substation restoration. Each information acquisition from supervisory system occurs individually.

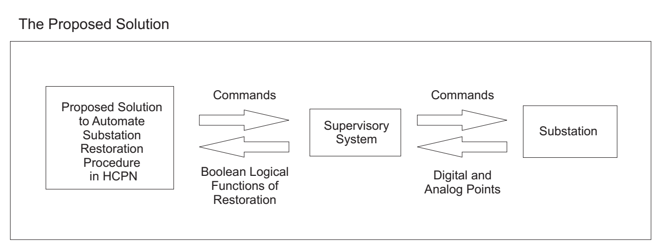

Fig. 2. The Proposed Solution.

In order to understand the problem to restore a substation, a real substation case is considered. In Figure 3, the simplified one-line diagram of the Sobral III substation can be observed. Note that, in Figure 3, the red color represents the 500 kV voltage level and the blue color represents the 230 kV voltage level. On the bay [2] designations, observe that ”5” refers to the 500 kV voltage level and ”4” refers to the 230 kV voltage level.

After a substation blackout, the needed commands to accomplish the substation restoration are oriented through the operational procedures [14]. These operational procedures state, initially, some conditions which characterize the substation blackout. Therefore, some conditions must be observed to start the structured sequential commands in order to restore the substation.

After studying and analyzing the items of the operational procedures which describe the conditions which characterize the blackout occurrence, the structured sequential commands and in order to present the solution formulation of the problem to restore a substation through the formalism in HCPN, becuase of space limit, part of the items to restore a substation is described in details as follows.

1) Identify the blackout occurrence through lack of voltage and loading non-existence;
2) Confirm or select the Human-Machine Interfaces (HMIs) to operate through Level 2 [3] (L2);
3) ”*Reset*” commands on the block relays in the following order: *15V9*, *15D1*, *15V7*, *15V8*, *15D2*, *15V6*, *15T1*, *15D3*, *14T1*, *14L2*, *14L3* and On Load Tap Changer (OLTC) of the *05T1*.

Relations between items 1, 2 and 3 of the operational procedures which state the needed commands to accomplish the restoration plan and some needed modelings to achieve these procedures are presented as follows.

- Item 1 → Modeling of the Substation - State;
- Item 2 → Modeling of the Substation - Control;
- Item 3 → Modeling of the ”*reset*” commands for the block relays in the following order: Bay 5A - Circuit Breakers - 86l, Bay 5B - Circuit Breakers - 86l, Bay 5C - Circuit Breakers - 86l, Bay 4B - Circuit Breaker - 86l, Bay 4D - Circuit Breaker - 86l, Bay 5C - OLTC - 86c.

In Figure 4, a diagram which represents the connection among the modelings of the proposed solution in this work is presented. The execution of these models starts on the modeling Substation - State. The arrows state the order in which the models execution occurs. In this Figure, the execution order of the proposed solution can be observed.

After analyzing and in order to formulate and solve automation problem of the operational procedures to restore a substation, some basic elements are realized to be ”indispensable” to model, e.g., circuit break, oltc, substation state and control substation. After modeling the ”indispensable” basic elements, some techniques to integrate these smaller models in bigger models are needed.

Before introducing the modeling of substation state, the concepts of the boolean logical function and the boolean logical function of restoration are important to be presented. Therefore, these concepts are defined as follows.

In order to exemplify and define the boolean logical function, the pre-condition ”Non-interlocked locally to ”reset” command of the 86l block relay” is taken as reference. This pre-condition is a function of the respective events associated to this pre-condition: ”Panel 5UA1BZ-1 - Control Unit 1 in Local” and ”Panel 5UA1BZ-1 - Control Unit 1 in Test”. The choice of this pre-condition as reference is due to the fact that this is a simple and representative example and didactically more interesting because there are just two events associated to this pre-condition and, therefore, it is not a trivial example with only one event associated to the pre-condition. Observe that the event ”Panel 5UA1BZ-1 - Control Unit 1 in Local” is alarmed as it is in logical level 1, whereas the event ”Panel 5UA1BZ-1 - Control Unit 1 in Test” is alarmed as it is in logical level 0. Considere the pre-condition ”Non-interlocked locally to ”reset” command of the 86l block relay” as being the variable ”y_2”, the event ”Panel 5UA1BZ-1 - Control Unit 1 in Local” as being the variable ”x_{21}” and the event ”Panel 5UA1BZ-1 - Control Unit 1 in Test” as being the variable ”x_{22}”. The boolean logical function of this pre-condition, y_2, is $y_2 = x_{21} + \bar{x_{22}}$. Observe that if the event ”Panel 5UA1BZ-1 - Control Unit 1 in Local” or the event ”Panel 5UA1BZ-1 - Control Unit 1 in Test” is alarmed, the boolean logical function ”y_2” will be in logical level 1 which represents that there is a token on the associated place to this pre-condition. If both events are not alarmed, the boolean logical function ”y_2” will be in logical level 0 which represents that there is not any token on the associated place to this pre-condition.

Similar analysis can be accomplished on the other pre-conditions to observe the behavior of the respective boolean logical functions associated to these pre-conditions.

Generalizing, the boolean logical function is associated to the acquisitions of the needed pre-conditions to accomplish commands on the equipments of the proposed model in this work and is $y_n = x_{n1} + x_{n2} + ... + x_{nm},$ where n and are integer numbers. Note that the integer number - n - is associated to the needed respective pre-condition to accomplish commands on the equipments. Observe that the integer number - m - is associated to the pre-condition respective events to which is related.

The boolean logical function of restoration is a boolean logical function OU of the respective boolean logical functions associated to the needed pre-conditions to accomplish commands on the equipments.

Generalizing, the boolean logical function of restoration of the proposed model in this work is $z_r = y_1 + y_2 + ... + y_s,$ where r and s are integer numbers. Note that the integer number - r - is associated to the respective transition which

[2] Bay is an used term in electrical engineering to designate the set of equipments in a power system (circuit breakers, disconnect switches, reactors, transformers, etc) which belongs to a section of a substation. Transfer Bay (TB) is an used expression in electrical engineering to designate a section of a substation used when the transference of circuit breakers associated to the voltage level of this section is needed.

[3] An operational control level through the Supervisory Control and Data Acquisition (SCADA) system of the substation.

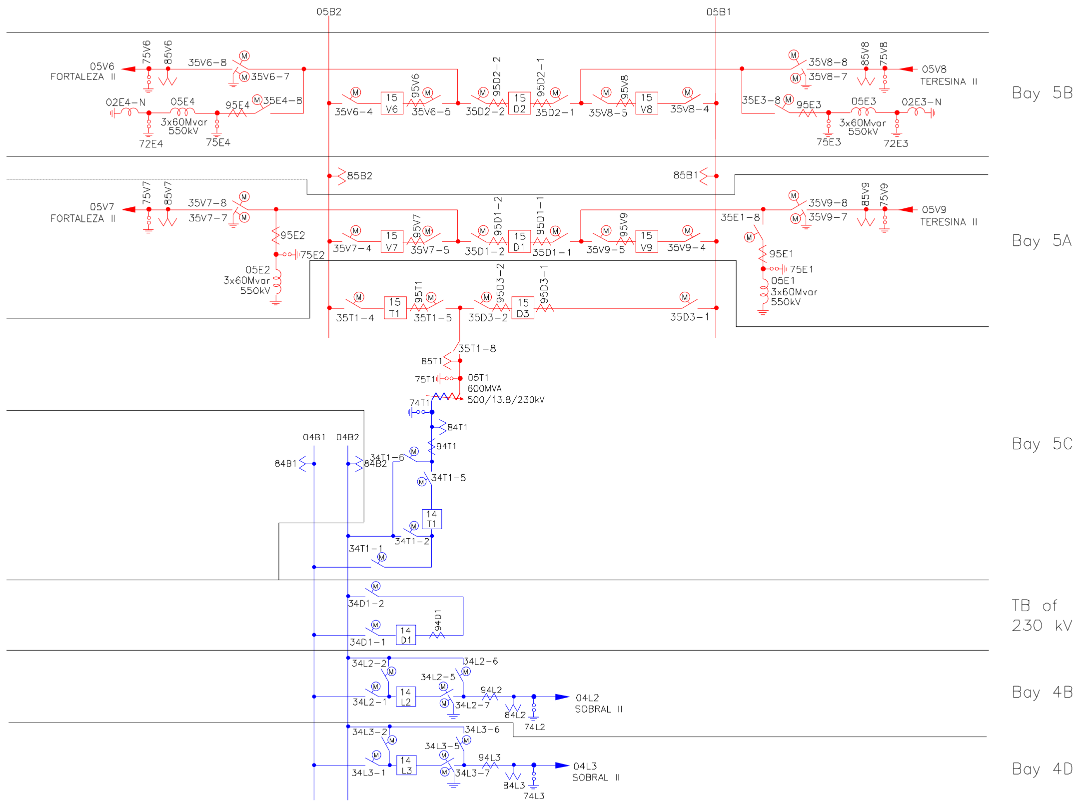

Fig. 3. Simplified One-Line Diagram of the Sobral III Substation.

acquires information from supervisory system. Observe that the integer number - s - is associated to the respective pre-conditions to which relate.

In order to present the proposed solution in this work to restore a substation, a substation state model - page ss_state - used in transmission systems of power system in HCPN is presented. Sobral III substation is taken as reference.

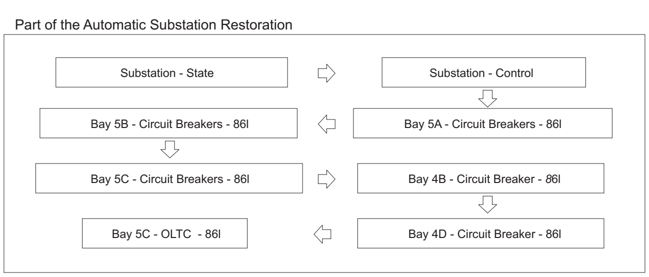

Fig. 4. Part of the Automatic Substation Restoration.

From the substation list of points, all the events (measurements and alarms) related to the substation were selected. After that, these points were studied and segregated in points which generate information about the substation state, associated to the substation measurements, and alarms, associated to this information about substation measurements. After this segregation, an analysis was achieved about all the needed pre-conditions to identify substation state as desenergized, according to the characteristics of the events, e.g., blocking and substation blackout. This analysis resulted in the following pre-conditions and their respective events.

- Non-blocked to start the substation restoration: *Digital System - Server 1 - Operating*, *Digital System - Server 2 - Operating*, *Panel 5UA8 - Control Unit 1 Fail*, *Panel 5UA8 - Control Unit 1 - Communication Fail*, etc [4];
- Substation blackout: *KV05B1 - Phase B* $\leq$ *30 kV*, *05B1 - Mini-Circuit Breaker (MCB) of the bar Potential Transformer (PT) Actuated*, *KV05B2 - Phase B* $\leq$ *30 kV*, *05B2 - MCB of the bar PT Actuated*, etc [5].

In HCPN modeling, each pre-condition of the substation state is modeled by a place which represents a specific pre-condition of the substation. A token in each place indicates that the pre-condition is satisfied. The presence of a token in each place is a function of the pre-condition respective events, i.e., a boolean logical function of restoration which is activated when any event of the related pre-condition occurs. The activation of a boolean logical function of restoration means that a token is present on the respective place related

[4]Some events are omitted because of space limit.
[5]Some events are omitted because of space limit.

to this pre-condition. Some events associated to the ”*status*” of the application are important. These events are important not only to complement the equipment modeling, but also aiming to the reliability and the safety of the application to restore a substation. If some pre-condition is not satisfied, a block alarm of the substation restoration automatism must be generated because all the pre-conditions are ”indispensable” to start the substation restoration automatism. If all the pre-conditions are satisfied, the substation restoration automatism is started. Therefore, the following events are needed.

- Start substation restoration automatism;
- Block of the substation restoration automatism;
- Non-block of the substation restoration automatism.

An important command to the dynamic of the substation state and its respective event are showed as follows.

- Command to start the substation restoration automatism: *Start Substation Restoration Automatism*.

In HCPN modeling, the command associated to the substation state is represented by a transition. A transition is enabled if all the pre-conditions represented by the respective ”input places” are activated. Therefore, this command can be accomplished. Substation state modeling is developed in CPN Tools. Sobral III substation is taken as reference. Substation state modeling to restore a substation automatically is composed by a page. This page is related to the substation state associated to the operational procedures, i.e., substation state which characterizes substation as desenergized. In Figure 5, modeling of Sobral III substation state in initial state is shown. This modeling is developed in CPN Tools. Places are associated to the needed pre-conditions to start substation restoration automatism and ”status” of the substation restoration application; transitions represent information acquisitions from supervisory system, decisions to dispose tokens and command order. A token in a place means this condition associated to this one is satisfied. There are mnemonics associated to some places and transitions which indicate what each place and transition represent: place *startrest*, e.g., indicates that the substation restoration automatism must be started; transition *startrest*, e.g., indicates to start the substation restoration automatism. Similar analysis can be accomplished on the other places and transitions to obtain the meanings of mnemonics associated to these ones.

To start the substation restoration automatism, the following dynamic is needed.

- Place *startrest* $\rightarrow$ a token in this place indicates the substation restoration automatism needs to be started;
- Transition *aqssstartrest* $\rightarrow$ a token in place *startrest* enables this transition, indicating the information acquisition which ”authorizes” to start the substation restoration automatism is needed. If the substation restoration automatism must be started, an information (a,true) is returned. Otherwise, an information (a,false) is returned. The boolean logical function of restoration associated to the transition *aqssstartrest*, z_2, is:

$$z_2 = y_1 + y_2. \tag{1}$$

Where:

y_1 is the boolean logical function associated to the pre-condition ”Non-blocked to start the substation restoration” of the Sobral III substation state;

y_2 is the boolean logical function associated to the pre-condition ”Substation blackout” of the Sobral III substation state;

- Place *aux1* $\rightarrow$ according to the information which ”authorizes” to start the substation restoration automatism, there is a token (a,true) in this place if the automatism must be started or a token (a,false) if the automatism must not be started;
- Transition *aux1* $\rightarrow$ this transition evaluates the obtained information about the ”authorization” to start the substation restoration automatism. This information is needed to start the automatism in a reliable and safe way. If the automatism must be started, a token *a* is added to the place *aux4*, indicating this. This enables the transition *startrest*, indicating the substation restoration automatism start is needed. However, if the automatism must not be started, a token *a* is added to the place *blockautom* and a token *a* is removed from the place *nblockautom*, indicating a block of the substation restoration automatism and any command can be achieved by the automatism due to reliability and safety criteria of the proposed solution;
- Place *aux4* $\rightarrow$ similar functionality to the place *startrest*, indicating all the needed pre-conditions to start the substation restoration automatism are satisfied. A token in this place enables transition *startrest*;
- Transition *startrest* $\rightarrow$ accomplishes the substation restoration automatism start;
- Place *startrestok* $\rightarrow$ a token in this place indicates the substation restoration automatism start was accomplished successfully, enabling next step to the automatism through transition *startrestnext*. When this transition fires, a token is removed from the place *startrestok* and a token *a* is added to the place *sscont*, indicating the selection of the substation to operate by the level 2 must be achieved.

Note:

- In its initial condition, the place *nblockautom* has a token, indicating the application of the substation restoration automatism is not blocked;
- In its initial condition, the place *blockautom* has not any token, indicating the application of the substation restoration automatism is not blocked.

Observe that the names of the places and transitions are distinct, aiming to have a correct and efficient analysis as the formal analysis of the proposed model in HCPN is needed, e.g., state spaces analysis. With this page of the substation state to restore a substation, part of the problem to automate operational procedures of substation restoration is formulated.

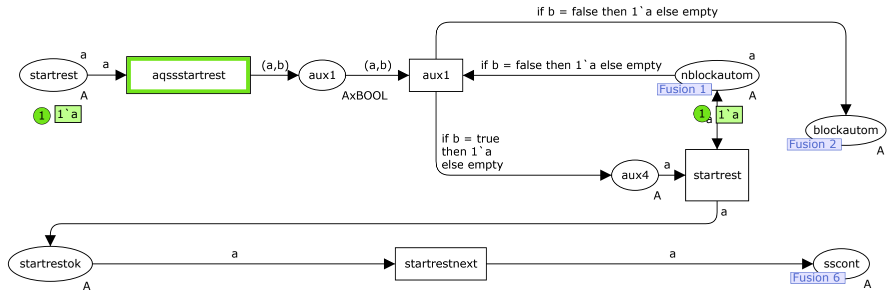

Fig. 5. Model of the Substation State Page in Initial State.

In Figure 6, the global model structure of the proposed solution is presented. In CPN, the complete operational procedures interpretation to restore a substation is transformed in sub-nets. In HCPN, the sub-nets - in a structured and scalable way - are composed in nets to formulate and solve the problem to restore a substation. The nets composition results in the global model of the proposed solution.

IV. Analysis

Initially, in order to facilitate analysis comprehension, in Figure 7, because of space limit, part of the state space [15] of the proposed solution is presented. The page name of the substation state modeling is ss_state. In this Figure, each node represents a reachable marking, whereas each arc represents the occurrence of a binding element, taking system marking from source node to destination node. In each node, there is a number in internal and superior side, indicating the respective number associated to this marking. By definition, initial marking is 1. In each node, there are also two numbers separated by ":" in internal and inferior side: the left number indicates quantity of antecessor nodes and the right number indicates quantity of successor nodes.

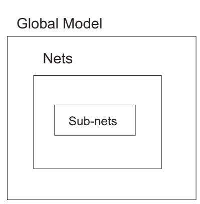

Fig. 6. Structure of the Global Model.

After presentation of Figure 7, analysis with ASK-CTL [16] can be introduced. A way to check modelings in HCPN is through a CTL-like temporal logic called ASK-CTL . In order to check a specific behavior of the proposed solution, a query code in ASK-CTL is described with its respective answer and a short explanation related to this code as follows.
Query 1:
val myASKCTLformula = NOT(MODAL(TT)) ;

eval_node myASKCTLformula 5 ;
Answer 1:
val it = true : bool
Query 1 and its respective answer mean marking 5 is dead.

Marking 5 is correctly a dead marking because this one is reached, e.g., from marking 3 when transition *aux1* fires with a binding element *b* = *false*, indicating the substation restoration automatism must not be started, according to the descriptions of Section III. This query through CPN ML functional programming language contributes to the proof of the proposed solution correctness. Similar analysis through CPN ML language can be accomplished about some behaviors of the proposed solution if a better comprehension of the modeling dynamic proprieties is needed.

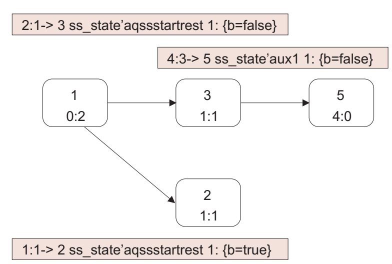

Fig. 7. Part of State Space.

Another way to analyze formally the proposed solution is to validate this solution with simulations of test cases. Consider a scenario of a substation blackout occurrence. After that, the application to restore a substation is started. In Figure 8, a Message Sequence Chart (MSC) associated to this simulation is shown. In this MSC, nodes in the superior side with associated descriptions represent places of ss_state page, whereas arrows with associated descriptions represent fired transitions of the modeling; reading must be achieved in top-bottom and left-right way because time reference is stated at this way. Therefore, a correct behavior of the proposed solution can be observed with this test case. This test case contributes to the proof of the proposed solution correctness.

Analysis of solutions in HCPN is important. This proves and values the proposed solution. It can also detect some problems in operational procedures to restore a substation. Checking and validation make this solution safe and reliable.

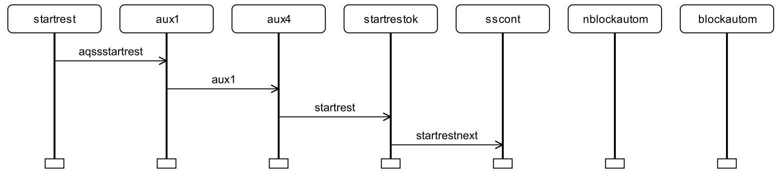

Fig. 8. Message Sequence Chart of Substation State Modeling.

V. Conclusion

The proposed solution in this work to restore a substation, using HCPN, is safe, reliable, fast and efficient. HCPN guarantees solution correctness. This becomes this solution safe and reliable. Solution dynamics makes this solution fast. This solution executes its task without time loss and in a correct way. This becomes this solution efficient.

The use of HCPN to formulate and solve the problem to restore a substation is justifiable due to complexity, i.e., representation of the complex dynamic of a DES in formal languages; methodology, i.e., possibility of easy generalization due to the solution to be structured and systematized; scalability, i.e., scalable solution in a graphical mode.

The solution presented in this work has the advantages of not having difficulty of representing a knowledge base and/or projecting an efficient mechanism of inference to determine which actions have to be taken, from a large volume of knowledge based on rules; not having bad performance, working with multiple faults; not having dependency of operator knowledge; being robust, i.e., if a problem to acquire some information or command some equipment occurs, alternative ways to accomplish substation restoration successfully are considered. Moreover, this solution is structured and systematized, causing an easy generalization and facilitating a possible maintenance and/or ampliation of this system; considers the detailed models of the substation equipments; is possible to integrate in a real case as a real substation is considered to develop this solution; considers the problem related to acquisition time and processing time of the information to take decisions as the synchronism dynamic between the proposed solution and supervisory system is discussed.

Using logical modeling with HCPN, it is possible to represent in a concise, detailed, direct, structured and practical way the dynamic behavior of the substation. Synchronism dynamics between the proposed solution and supervisory system makes information to be processed updated. This solves the problem related to acquisition time and processing time of the information to take decisions. The boolean logical function of restoration definition introduced in this work simplifies substation information and therefore facilitates formulation and solution of the problem to automate substation restoration procedures. With a solution in HCPN, formal methods to check - complete state space and ASK-CTL temporal logic - and validate - simulations and MSC - are possible. The analysis developed in this work is useful to prove and value the proposed solution. This analysis can also detect some problems in operational procedures to restore a substation.

The proposed solution in this work provides an important contribution to the substation restoration automatism. It can be used by electrical companies what can represent relevant financial and operational gains.

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