Impact Assessment of Substations Configuration on Power Systems Security

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Impact Assessment of Substations Configuration on Power Systems Security

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SUMMARY

Protection system failure is one of the main causes of cascading outages, almost the 65% of major disturbances. This document presents a technique which combines Petri Networks, operating states, and building blocks theory to analyze, study, and measure the impact of protection system failures in substations in terms of adequacy, security, and reliability. As well, this technique allows to simulate the connection between substations with different configurations. The methodology is demonstrated with seven configurations of substations, such as: single bus, single bus with Tie breaker, main and transfer buses, single bus - double breaker, ring bus, breaker-and-a-half breaker, and double bus-double breaker.

Resumen. *Las fallas en sistemas de protección son una de las principales causas de eventos en cascada, aproximadamente el 65% de los más importantes apagones en Estados Unidos. Este documento presenta una técnica que combina teoría de Redes de petri, estados operacionales de sistemas de potencia y construcción de bloques, para analizar, estudiar y medir el impacto que tienen las fallas de sistemas de protección en subestaciones, en términos de capacidad, seguridad y confiabilidad. Asimismo, esta técnica permite simular la interconexión entre subestaciones con diferentes configuraciones. La metodología es demostrada y aplicada con siete diferentes configuraciones de subestaciones, tales como: barra sencilla, barra sencilla con breaker de conexión, barra principal y de transferencia, barra sencilla con doble breaker, configuración en anillo, breaker y medio y doble bus - doble breaker.*

CHAPTER I

INTRODUCTION

Electrical power systems provide electricity supply to a considerable amount of people around the world. There are three main processes in order to deliver that electricity to end users, those are: generation, transmission, and distribution, they work as a chain process, where each one requires to bring a reliable, secure, and stable service. Therefore, there is an increased interest for developing tools that allow the security evaluation of power systems, and also to ensure high levels of quality, reliability, and availability. However, these levels are affected by some factors that have been recognized as contributing elements in order to lead to catastrophic and cascading events, such as: uselessness and hidden failures of protections in Power Systems. Nevertheless, those can be modeled as probabilistic events, which can be calculated taking into account the operating sequences, considering the following operating states: normal, alert, emergency, extreme emergency, and restorative [10].

According to the NERC 2008 annual report [24], equipment failures are involved in about the 23% of major disturbances, and protection misoperations are involved in about 42% of major disturbances. Thus, the protective system plays an important role in power system operation, and a very important role in causing cascading events. However, there are still major blackouts in spite of technological advances and huge investments in system reliability, adequacy, and security.

For that reason, it is important, besides reinforcing the protection systems, to develop new tools to analyze, study, and measure the impact of determined protection system failures in terms of adequacy, security, and reliability. Thus, researchers have proposed several models for reliability and security evaluation of substations [9, 28, 30]. However, the main weakness is to forget the impact of a substation fault over neighbor substations, as well as the uncertainty in the appropiate response of the protective systems.

In the set of protection devices, circuit breakers are very critical components, because they are the last barrier to protect other devices of a Power System against faults. Thus, a detailed study of these devices allows to find the root causes and dynamics of cascade events in Power Systems. As well, it is important to quantify the probability of failure of the whole system to asses the risk to lead a voltage collapse, taking into account the performance and, even more, the unreadiness of the breakers [3].

Substations have always been modeled as a single bus bar [5, 31]. Furthermore, all the circuits connected to the substation trigger when a system fault is simulated. Also, there are many different configurations of substations, e.g. single bus, ring bus and breaker-and-a-half bus [20]. So, when a fault occurs in the system, not all the protections trigger. Therefore, cascade events studies are incomplete without considering different configurations of substations. Therefore, it is necessary to develop a tool that can be able to evaluate and analyze in detail the effect of protections in substations with different configurations, and also able to measure the impact of the protections over the Power System.

Petri Nets theory allows the evaluation of the Power Systems Security, considering the system response to sudden disturbances produced by short circuits and component outages, and the computation of operating state probabilities considering the probability of the appropriate operation of each protection device.

The aim of this document is to present the impact of protection failures on a Substation with different configurations or schemes, and how a contingency can lead to cascade events on other substations. This will help to identify high-level conclusions and recommendations for improving system dynamic performance and reducing the risk of such catastrophic events. Thus, maintaining an adequate level of system reliability and security, minimizing the risk of major blackouts resulting from cascading outages led by a single disturbance.

The proposed analysis looks at the events: how, when, and in what order they occur. Each answer provides detailed information in order to analyse the substation behaviour and the security of the system. Such analysis is summarized in tables, which show the different sequences after a failure of a protective system, and how a single failure leads to a cascade event. All these outcomes allow planning and designing better, more reliable, and more secure systems.

CHAPTER II

MAIN CONCEPTS

2.1 Power System Operating States

Operating states of power systems were proposed by Fink and Carlsen in 1978 [10]. They divided the operating states of the power systems into five stages, those are: Normal, Alert, Emergency, In Extremis, and Restorative. Their interactions are showed in Figure 1. These states were defined as follows:

- Normal: The system operates satisfying all the constraints of the system, so that all substations can supply the load demand that is required to ensure the proper functioning of the system. None of the protective equipment or lines are being overloaded.
- Alert: The system is still operating, but some operating constraints are not met within the system as a result of the overloading of some protective system. In this state should be carried out corrective actions to avoid a blackout in the system and thus return to normal state. For non-controlled transitions, there is a reduction in the security level. Therefore, the system is susceptible and vulnerable to subsequent interruptions. It is possibly due to either unexpected increases in loads, not boot-generating machines, loss of generating units, loss of transmission lines, or increased levels of risk due to storm or natural disasters.
- Emergency: System constraints have been exceeded, these constraints are related to some of the following variables: voltage levels, system frequency, and angles of machines or buses. The security level is low, therefore control measures should be undertaken to bring the system into the alert state. However, the system is still intact.
- In Extremis: In this state the constraints of the system have been violated, and the system has lost significant loads. Thus, the system is not still intact. Actions must be undertaken to restore the supply to all loads making reconnections.
- Restorative: After taking control action in the system. It is reconnected, and the loads are returned.

However, the analysis shown above was improved by various research groups [1] y [16]. They basically added new transitions between the different states. Thus, one of the most complete diagram is found in [4], which associates the different states as shown in Figure

2. This diagram has transitions from normal state to the state of emergency, and from normal state to extreme emergency state. Likewise, it adds a transition between alert state and extreme emergency state. It is important to mention that the fourth state changed its name, from In-Extremis State to Extreme Emergency State.

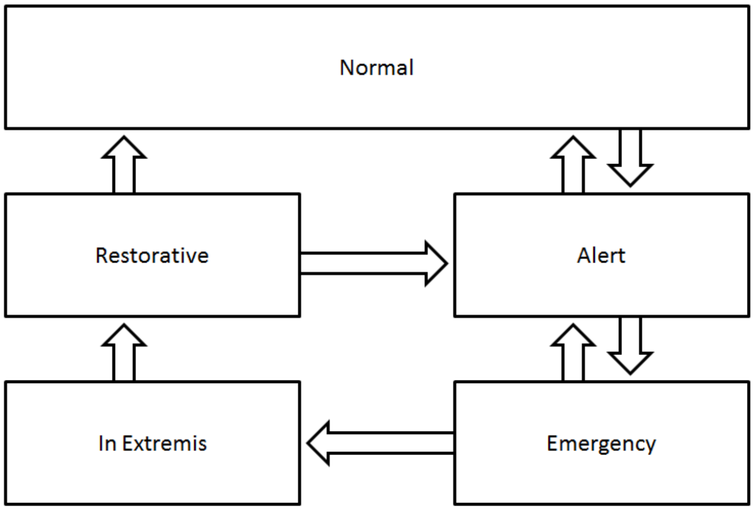

Figure 1: Operating States according to [10]

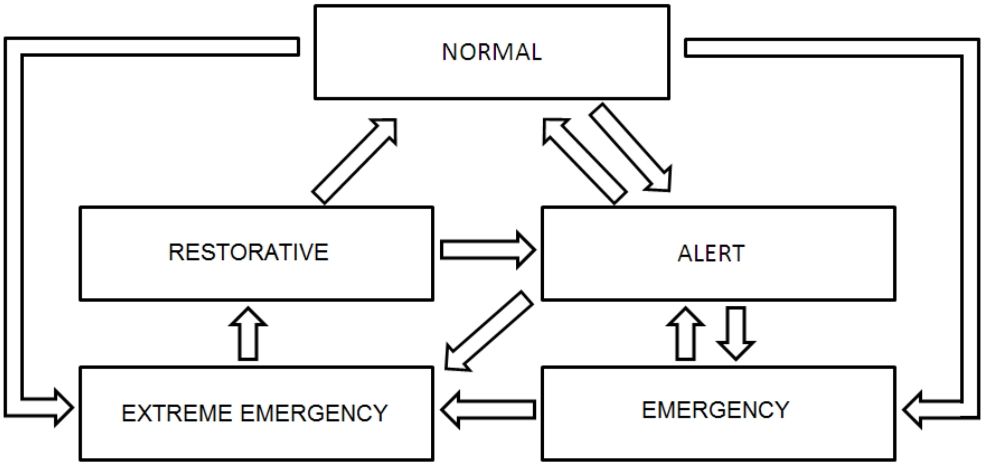

Figure 2: Operating States according to [4]

2.2 Petri Networks (PN)

Petri Nets is a tool developed by C.A. Petri in 1962 [26], and it was designed in order to study different systems [25]. The theory of Petri Nets allows to make a mathematical model of a system, allowing to know important and relevant information about the structure and the dynamics of such system [8].

Many systems can be studied using Petri Nets, such as: concurrent, asynchronous, distributed, parallel, non-deterministic and stochastic. For that reason, it is a flexible tool to analyze many industrial processes, i.e. production plants, modeling of electrical devices and computing systems [23]. Thus, there are many studies concerning Petri nets in Power Systems, such as: modeling of security protocols [15], routing of AD/HOC networks [36], sequences of protections in looped power systems [33] and protections in Electrical Industrial Systems [32].

A Petri Net is a particular kind of bipartite directed graph that comprises several sets, which are nodes and arcs. Nodes are divided into places (P) and transitions (T), which represent the states and events that allow moving from one state to another. Each element has its respective set. For instance, for transitions: $T = \{t_1, t_2, t_3, ...\}$, and for places: $P = \{p_1, p_2, p_3, ...\}$. Arcs connect places with transitions and vice versa [23].

There are also Tokens, that show graphically the availability of places. The Tokens are those dots inside the places into the net. Figure 3 shows the main elements on Petri Nets.

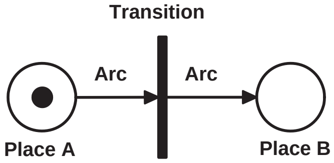

Figure 3: Petri Nets representation

Firing a transition consists in moving the token from one place to another. Figure 4 [8] shows some possible transitions. For instance, figure (a) shows how the places p3 and p4 are activated. In the case of figure (b), due to the presence of a token in the place p3, now this place has two tokens. Figure (c) shows the case where the place p1 had two tokens, and after firing the transition T1, this place has only one token.

Some behavioral properties of Petri Networks are [17, 23]:

- Parallelism and Concurrency: The different activities of one component of a system can occur simultaneously with other activities of other components.
- Reachability: A state m_1 is reachable from an initial state m_0, specifically in the case of the Figure 3, the state m_1 (Place B) is reachable by the state m_0 (Place A). This property is fundamental for studying the dynamics of any system.
- Boundedness: A Petri net is bounded if the number of tokens in each place does not exceed a fixed number defined by the designer.
- Coverability: All the places are covered by some other places that are reachable.
- Persistence: A Petri net is persistent if for any two enabled transitions, the firing of one transition will not disable the firing of another transition.

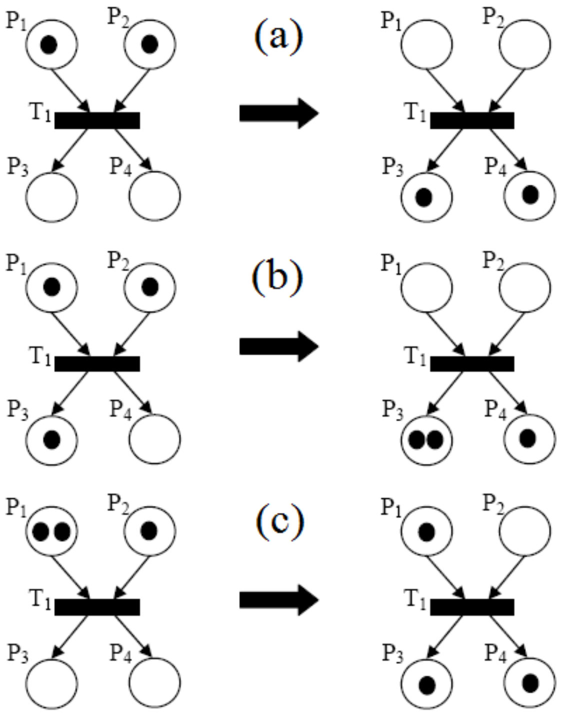

Figure 4: An illustration of some possible transitions firing

Reachability graph is a useful concept of Petri Nets, specifically of marked Petri Networks [23]. This model allows to evaluate the property of reachability in a Petri Net, i.e. all the markings which can be reached from a state through the firing of one or more transitions. Graphically, each node corresponds to a state, and the edges are associated with transition fires [6, 23], an example of such trees can be found in Figure 5.

Three types of Petri nets help to perform systems analysis [14]: the marked, timed, and stochastic Petri Nets. Marked Petri nets are mostly used to perform a quantitative measurements. These analyses will focus at the properties of conservativeness, safeness, and properness. Likewise, probabilities can be assigned in order to resolve conflicts when there are two or more possible transitions to be fired.

Ref. [34] recommends, for modeling large systems with Petri nets, to make smaller models of systems in order to create building blocks that can be connected with logic links that represent the whole system.

2.3 Substation Configuration Fundamentals[20]

Substation configuration is basically the arrangement of the electromechanical equipment constituting a yard of connections or elements belonging to the same level of tension, so that its operation would enable the substation to different degrees of reliability, safety or flexibility for handling transformation and distribution of energy [13].

There are two trends in terms of configurations of substations:

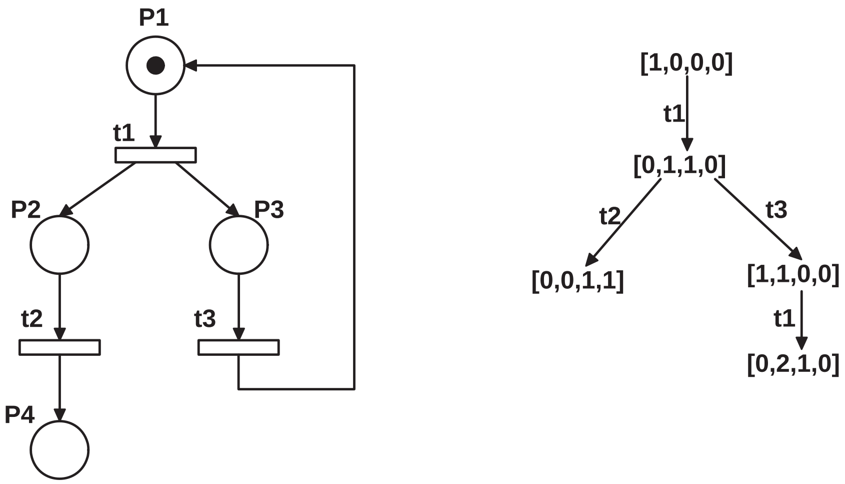

Figure 5: Petri Net and Reachability Tree

- European or bus connection.
- American or switch connection.

2.3.1 Bus connection configuration

2.3.1.1 Single Bus

Presented in Figure 6, the main properties of this configuration are:

- It has only one bus, and the circuits are connected to it through a single switch.
- It is economical, easy to protect, it takes up little space and does not have many chances of incorrect operation.
- The main disadvantage is the lack of reliability, security, and flexibility.
- During normal operation, the circuits can not be changed from one bus to another.
- It is used mainly when there is either a single transmission line, a single transformer, or a shunt transformer.
- Not recommended for either high-load substations or essential substations for the correct performance of the system.

2.3.1.2 Single Bus with Tie-Breaker

Presented in Figure 7, the main properties of this configuration are:

- Two single bus arrangements are connected together with a circuit breaker (Tie-Breaker).

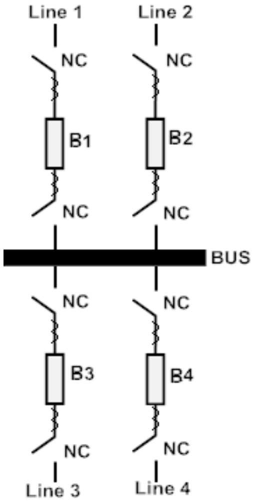

Figure 6: Single Bus Scheme of Protection

- If a breaker fails, the entire station does not shot down.
- Its main advantage is that this configuration allows the isolation of bus sections for maintenance.

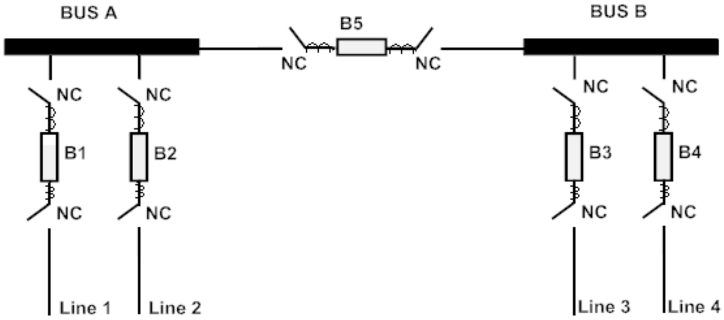

Figure 7: Single Bus with Tie Breaker Scheme of Protection

2.3.1.3 Main and Transfer Buses

Presented in Figure 8, the main properties of this configuration are:

- There are two separate and independent buses.
- All circuits are connected to main bus.
- If maintenance is required on a Circuit Breaker, the associated circuit can be supplied from the transfer bus.
- Its main disadvantage is that a bus fault causes loss of the entire substation.

- The transfer bus is not energized.

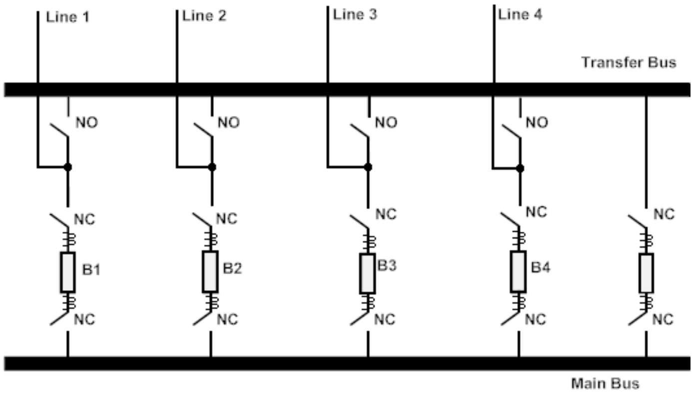

Figure 8: Main and Transfer Buses Scheme of Protection

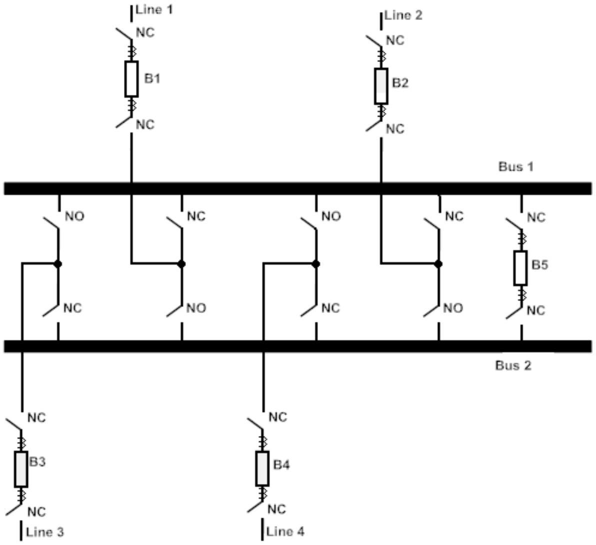

Figure 9: Single Breaker - Double Bus Protection Scheme

2.3.1.4 Single Breaker - Double bus

Presented in Figure 9, the main properties of this configuration are:

- Any line can be operated from either of the buses.
- It requires complicated switching of the protections.
- A fault on either bus requires tripping all circuits associated to the fault bus.

2.3.2 Breaker connection configuration

2.3.2.1 Ring Bus

Presented in Figure 10, the main properties of this configuration are:

- There are no buses.
- The connection of the circuit is done on the ring formed by breakers.
- To isolate a circuit is needed to open the two corresponding breakers, consequently opening the ring.
- This is an economical and secure configuration, as well as being reliable.
- Its main disadvantage is that if there is a fault in a circuit, the ring could be divided and may present a fault on any side.
- From the standpoint of flexibility, it is the same as a single bar.
- It can be connected the source and load interspersed along the ring. Thus, it minimizes the potential loss of sources of the ring due to a failure of any protection.

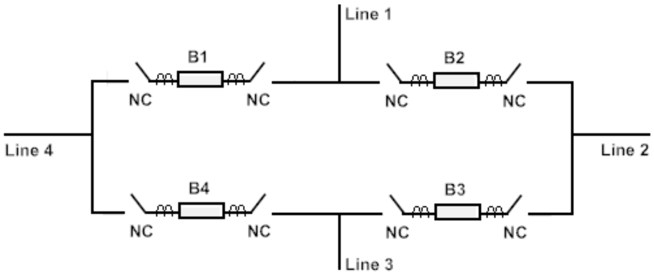

Figure 10: Ring Bus protection Scheme

2.3.2.2 Breaker-and-a-half bus

Presented in Figure 11, the main properties of this configuration are:

- Both buses are energized during normal operation.
- Requires three breakers for every two output lines sharing a common center breaker.
- Maintenance can be done to any breaker, without suspending the service, and without disrupting the protection system.
- A fault on a Bus does not interrupt service to any circuit, presenting a high level of reliability and security.
- If a center breaker fails, this will cause the loss of two circuits.

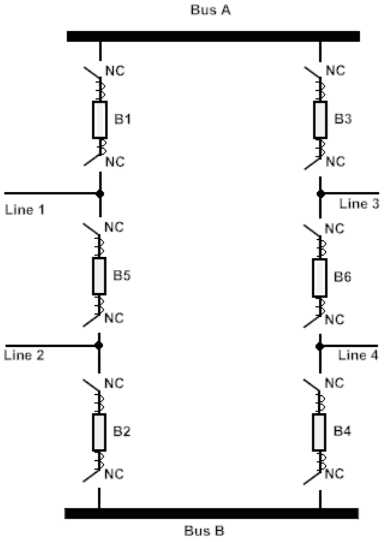

Figure 11: Breaker-and-a-half Bus Protection Scheme

2.3.2.3 Double Breaker - Double Bus

Presented in Figure 12, the main properties of this configuration are:

- It has two main buses that are both normally energized.
- This configuration doubles the breakers of each circuit.
- It presents the greatest security, very high reliability, and a flexible operation.
- In some cases, it can be divided into two groups, connecting each of the circuits to a bus.
- It is the most expensive of all configurations.
- It is usually used at large generating stations.

2.4 Blackouts, Hidden failures and Cascade events

Reference [29] presents the root causes and dynamics of American Major Blackouts. They conclude that most major blackouts are initiated by a single event. Figure[1] 13 shows the general sequence of events leading to a blackout. The single event could be an equipment failure, a line that trips due to relay misoperation, a line that trips due to tree contact, among others.

According to [11], there are two factors involved in major blackouts: deterministic and probabilistic factors. Deterministic factors include all causes that are generated from operation constraints which are determined by physical equations of Power Systems, e.g. overload,

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[1] Figure from ref.[29], fig 2, p. 26.

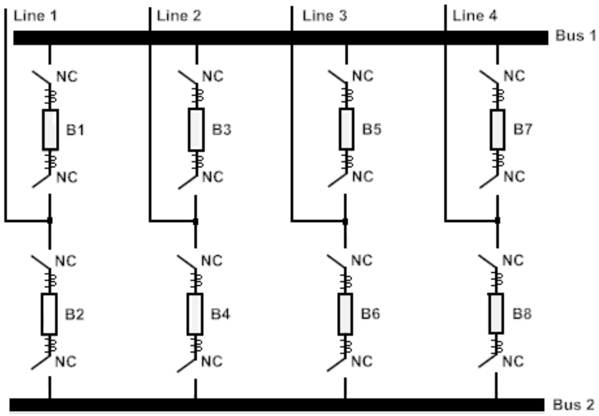

Figure 12: Double Breaker - Double Bus Protection Scheme

low voltage, over-current. On the other hand, probabilistic factors are solely decided by the reliability characteristics of devices, e.g. failure of the tap-changing mechanism, failure of back-up device, failure of communication channel.

After the initiating event, the next step is the remedial action which should be done in a very short time frame. If it is done correctly, the system starts a readjustment in order to reach a normal state. But, the initial event can lead cascading events if the remedial action does not isolate the initial event. Thus, the system reaches a point of no return, leading to a final stage of collapse and finally a blackout.

Within the initiating events are Hidden failures in protective systems, these are the effects that cause a relay or protective system to incorrectly and inappropriately remove a component, as well as the direct consequence of the commutation of another event [35]. Likewise, according to [27, 21], hidden failures in relays and protection equipment are one of the main causes of cascading outages.

However, the occurrence of a hidden failure can generate a cascade event, which is basically a sequence of failures of individual devices that successively weakens the Power System [2]. Although the origin of the cascade may be due to a random event or a hidden failure, there is a causal connection between the following events of the chain of cascading events. The combination of these multiple events leads to the collapse of the system.

To avoid cascading events, operators use tools that either in real time or in planning studies, allow to study the consequences of a particular fault and how these can be mitigated. In order to simplify the problem, each failure is studied separately, and the interactions between the different phenomena are often ignored.

For the study of cascades, there are some types of studies or analysis [2], such as probabilistic and deterministic approaches, development of potential risks, networks theory, probabilistic models of high-critical components of multiple contingencies, pattern recognition, conventional methods of reliability studies, among others. Given the objectives of

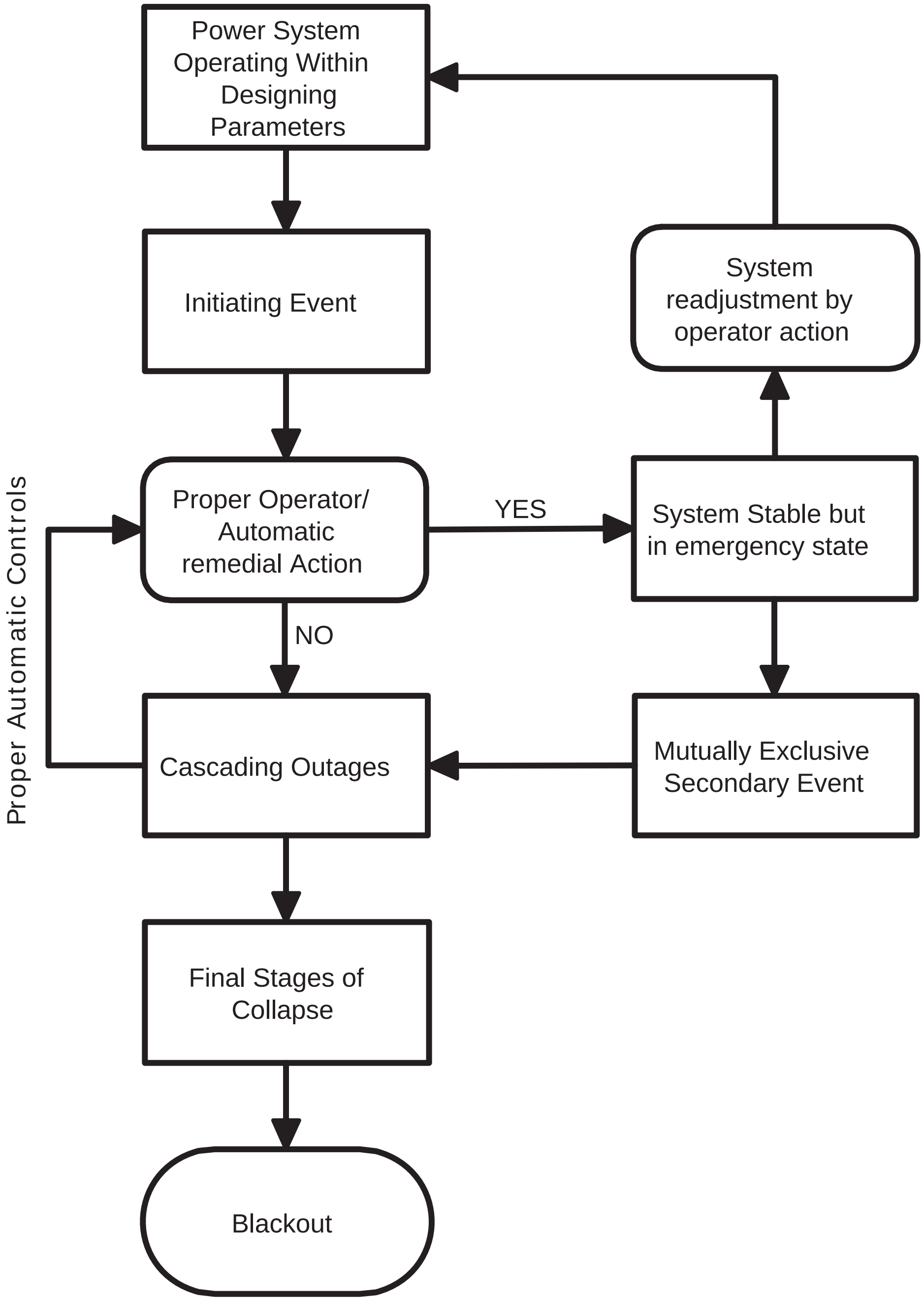

Figure 13: General sequence of events leading to a blackout [29]

this study, it is taken into account the analysis of cascade events with high-level probability models, which describes the process of cascade without considering the physical model of the Power System, and also without considering the times between cascades. Thus, it is a useful model for understanding the cascading events of the Power Systems, specifically the different topological configurations of substations.

To simulate the cascading events, researchers have focused on different objectives such as: protection, operator actions, voltage collapse, on-line analysis, industrial applications, islanding, dynamic simulations, among others. Some studies relating to these objectives are: About actions of operators and guards in simulation [12] refers to the experience at Southern Company in United States where they have experienced various cascade events; therefore, they have developed a new methodology that can simulate cascade events, evaluate the impacts of these on the system and perform a ranking of the different scenarios. [22] describes the methodologies for calculating the risks of catastrophic failures in the Power System Networks due to hidden failures in protective systems, leading to voltage collapse.

2.5 Related Works

In reference [14], Jenkins modeled protection schemes using Stochastic Petri nets, taking into account main and backup protection. Likewise, he makes a study of different types of Petri nets that can be applied to study the behavior of the protections. Nevertheless, he made this analysis without considering uncertainty in the appropriate response of the protection device. This document has been a primary source of advice for researchers who wish to conduct such studies.

Reference [33] presents sequences models of protections using Petri Nets, where was obtained a methodology for modeling looped distribution systems. The methodology is summarized in Figure 14.

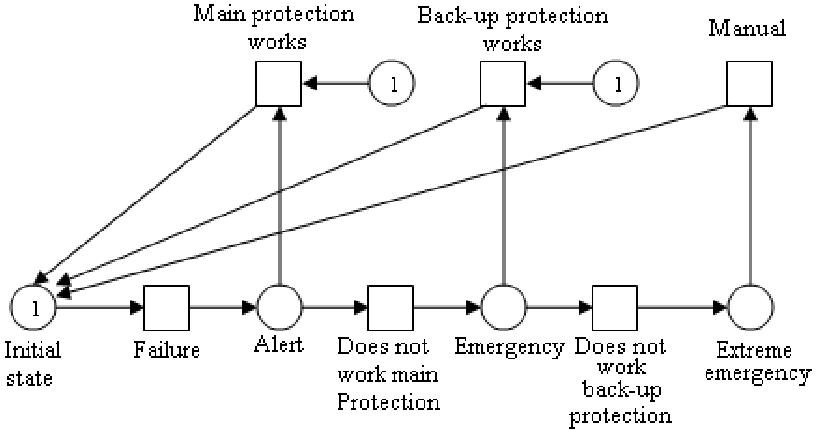

Figure 14: Proposed Methodology for PN Models of Protection Systems [33]

Reference [28] studied the coordination of control functions and automation in substation of transmission systems, this was one of the first studies on the topic. However, computational limitations were found, when trying to ensure a stand-alone feature on the control devices, taking into account time, testing and data sequences into the system.

The study of different types of configurations and substation reliability analysis was evaluated with the aim of answering one question: When an existing substation is not reliable? [9].

This document is interesting, because it gives values of MTTR[2] and failure rates of individual components that are part of a substation. For instance, the MTTR for a main transformer is 356 hours (2 weeks), for a 480V-Fuse a MTTR of 2 hours. On the other hand, they evaluated six different configurations of substations, which are single radial configuration, single bus with double feeding, double breaker - single bus, double bus - double breaker, among others. Finally, a conclusion of their results is that the less reliable configuration is single bar. On the other hand, the most reliable is the configuration of double bus - double breaker.

Likewise, they have developed new methods for studying protection in substations, such as the reference [18], in this study, they take into account main and backup protection in the substation. They conclude that the method is very fast and useful for the study of the protections.

Finally, PSERC[3] completed a study, published in February 2009 [30], where is done a study of N-k contingencies selection. More specifically, it is a study for estimating the reliability of different configuration of substations such as: single bus, ring bus, double breaker - double bus, and breaker-and-a-half. To do this, they used mathematical tools, which allows to estimate probabilities according to the types of connections in each configuration.

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[2] MTTR: Mean Time To Repair.

[3] PSERC: Power Systems Engineering Research Center.

CHAPTER III

MODELING SUBSTATIONS WITH PETRI NETS

3.1 Methodology

As in any power system, the relationship of all possible operating states of the system can be modeled by stochastic transitions. Therefore, taking into account the system responses, it could be defined the following operating states: normal, alert, emergency, extreme emergency, and restorative [10]. Figure 2 shows the establishment of transitions between these operating states. In consequence, if the system is in normal or alert state it could be stated that the system is secure; on the other hand, the system is in a non-secure state if it is in emergency or extreme emergency state.

The main components to define the operating states of the Power Systems are the protective devices, such as: breakers, UPS, filters, among others. In the same way, the main events used in the PN formulation are: short circuits, interruption of energy supply, and power quality problems [31].

Taking into account the sequence operation of protective devices when a sudden disturbance occurs, the unreadiness probability, or the probability of non response of the protections when they are needed, is equivalent to the conditional probability of non-operation when the disturbance is present.

In Power Systems, the non-secure probability is computed from the probabilities that the system reaches an emergency or extreme emergency state, when a sudden disturbance occurs (such as a short circuit) as function of the operation of main and back-up protections.

The first step to assess the security of substations is to create and simulate the Petri Network corresponding to all possible faults in the Power System, i.e. faults on lines and on Buses. Therefore, the cascade events can be evaluated according to the following algorithm, see Fig. 15:

1. Choose the possible failure: There are many possible failures in the system. So, it is important to decide which one will be modeled. For instance, fault on Main Bus in a Main-and-transfer buses configuration.

2. Choose the element to be analyzed: Because there are many lines, the designer must choose in which line will focus its study. For example, to assess the probability of occurrence of a cascade event through the line 1.

3. Select the possible cascades: According to the protection zones of the different breakers, the designer should decide which could be the breakers implicated in a cascade

event due to the failure chose in step 1.

4. Create the Petri Network: After selecting the initial point of the cascade, the final point, and the possible protection devices implicated in the cascade, the designer can create the Petri Net according to the sequence of protection that trigger in order to avoid a cascade event through the selected line.
5. Assign an operating state for each place in the Petri Net: There are specific places that can supply important information about the system, so an operating state must be assigned to each one of those places in order to assess the probability of occurrence of the operating states.
6. Simulate: The Petri Net is simulated in the Petri Net Toolbox 2.3 for Matlab [19].
7. Security index assessment: For each one of the Substation modeled, a probability of occurrence of a cascade event through the element selected in step 2 is computed.

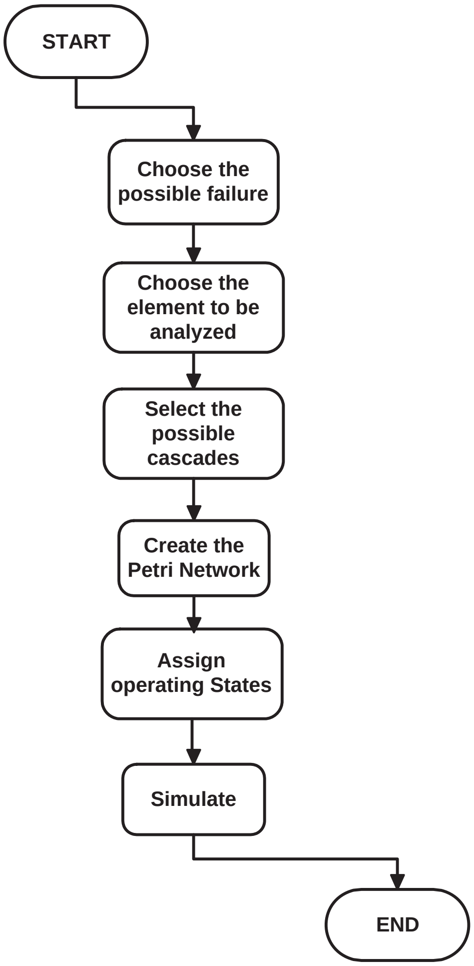

Figure 15: Methodology for modeling Cascade events in Power Substations

3.2 Applications

The seven basic configurations of substations considered in this paper are defined in Table 1. For the present study, all substations have been connected to 4 lines, in order to compare the substations in similar conditions. The failure probability of each protective system when it is required to operate is 5%, and the number of trials for each simulation is 5000, which ensures an error lower than 5% with a 95% confidence interval.

Name	Number of Breakers
Single Bus	4
Single Bus with Tie-Breaker	5
Main and Transfer Buses	4
Single Breaker-Double Bus	5
Ring Bus	4
Breaker-and-a-half Bus	6
Double Breaker double Bus	8

Table 1: Basic Substations Configuration Analysed

3.2.1 Single Bus Substation

3.2.1.1 Fault on Main Bus

As was described in the configuration bar, Figure 6, any simple fault protection generates the disconnection of all lines connected to the bar. Figure 16 presents the Petri Net for the Fault on Bus in the Single Bus Substation configuration. Tables 2 and 3 show the places and transitions of the PN, respectively.

Place	Description
P1	Normal operation
P2	Fault on Bus
P3	Fault on Line 1

Table 2: Places of the Single Bus Configuration PN, Fault on Bus

After simulating the PN presented in Fig.16, the fault leads to a cascade event on Line 1 in the 5% of the cases. That can be seen because there is only one bus and the fault has only one way in order to lead an outage in line 1. This confirms the lack of flexibility, and reliability of the single-bus configuration.

Transition	Description
t1	Fault on Bus
t2	R1 trigger correctly
t3	R1 failure

Table 3: Transitions of the Single Bus Configuration PN, Fault on Bus

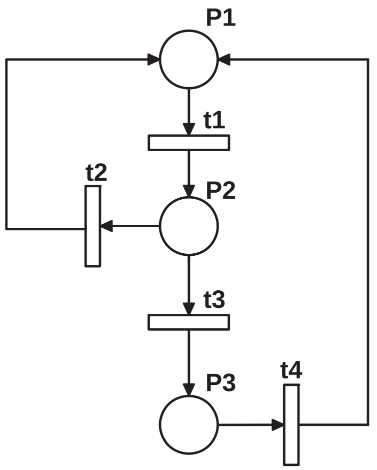

Figure 16: PN for Single bus configuration, Fault on Bus

3.2.1.2 Fault on Line 4

Figure 17 presents the Petri Net for the Fault on Line 4 in the Single Bus Substation configuration. Tables 4 and 5 show the places and transitions of the PN, respectively. It is the same Petri Network for all line faults. After simulate the PN presented in Fig. 17, the fault leads a cascade event on Line 1 the 4.7% of the cases.

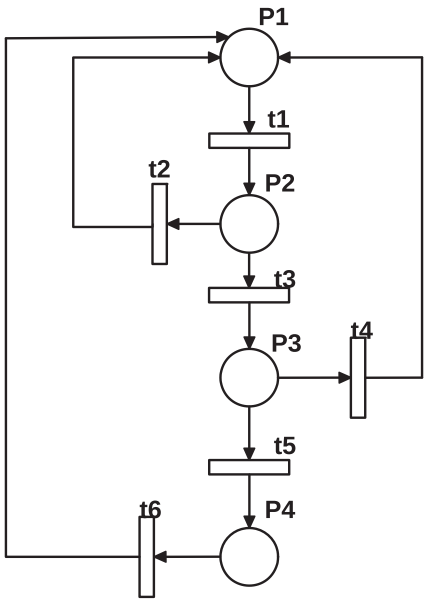

Figure 17: PN for Single bus configuration, Fault on Line 4

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Bus
P4	Fault on Line 1

Table 4: Places of the Single Bus Configuration PN, Fault on Line 4

Transition	Description
t1	Fault on Line 4
t2	R4 trigger correctly
t3	R4 failure
t4	R1 trigger correctly
t5	R1 failure
t6	Restorative

Table 5: Transitions of the Single Bus Configuration PN, Fault on Line 4

3.2.2 Single buses connected with bus tie-breaker Substation

3.2.2.1 Fault on Bus A

Fig.7 shows the single buses connected with bus tie-breaker Substation configuration, Fig. 18 presents the Petri Net for the Fault on Bus A in the Single buses connected with bus tie-breaker configuration. Tables 6 and 7 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 18, the fault leads a cascade event on Line 1 the 5.0% of the cases.

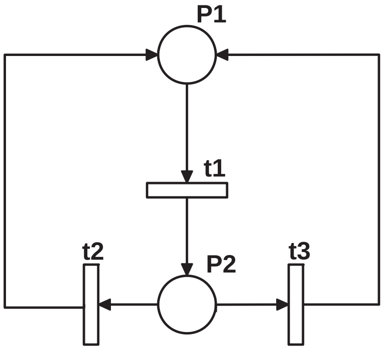

Figure 18: PN for ingle buses connected with bus tie-breaker configuration, Fault on Bus A

3.2.2.2 Fault on Bus B

Fig. 19 presents the Petri Net for the Fault on Bus B in the Single buses connected with bus tie-breaker configuration. Tables 8 and 9 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 19, the fault leads a cascade event on

Place	Description
P1	Normal operation
P2	Fault on Bus A

Table 6: Places of the Single Bus with Tie-breaker Configuration PN

Transition	Description
t1	Fault on Bus A
t2	R1 trigger correctly
t3	R1 failure

Table 7: Transitions of the Single Bus with Tie-breaker Configuration PN, Fault on Line

Line 1 the 0.3% of the cases.

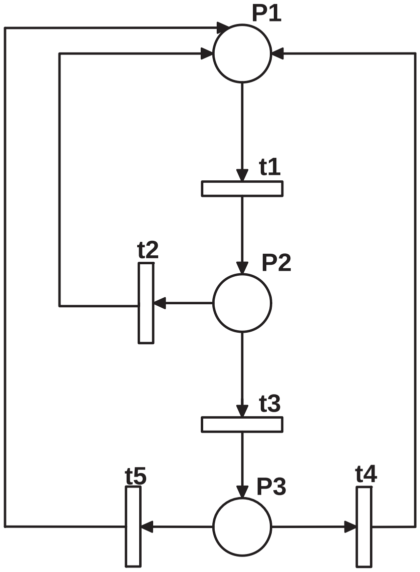

Figure 19: PN for ingle buses connected with bus tie-breaker configuration, Fault on Bus B

3.2.2.3 Fault on Line 2

Fig. 20 presents the Petri Net for the Fault on Line 2 in the Single buses connected with bus tie-breaker configuration. Tables 10 and 11 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 20, the fault leads a cascade event on Line 1 the 0.02% of the cases.

3.2.2.4 Fault on Line 4

Fig. 21 presents the Petri Net for the Fault on Line 4 in the Single buses connected with bus tie-breaker configuration. Tables 12 and 13 show the places and transitions of the PN,

Place	Description
P1	Normal operation
P2	Fault on Bus B
P3	Fault on Bus A

Table 8: Places of the Single Bus with Tie-breaker Configuration PN

Transition	Description
t1	Fault on Bus B
t2	Tie Breaker trigger correctly
t3	Tie Breaker failure
t4	R1 trigger correctly
t5	Tie BreakerR1

Table 9: Transitions of the Single Bus with Tie-breaker Configuration PN

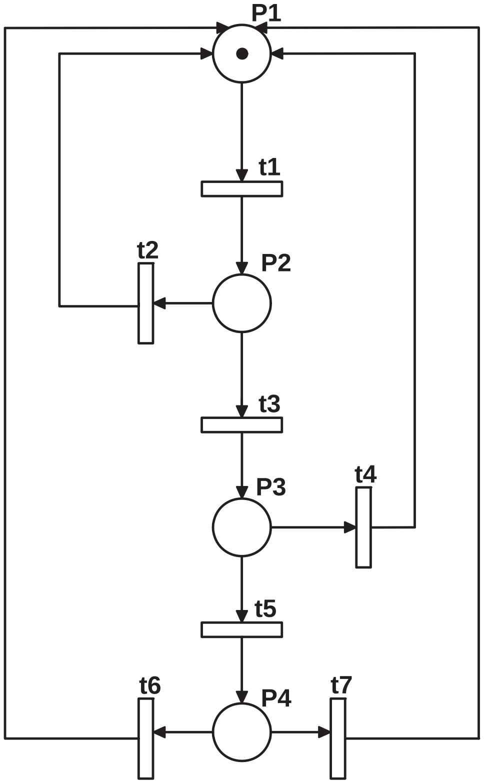

Figure 20: PN for ingle buses connected with bus tie-breaker configuration, Fault on Line 2

Place	Description
P1	Normal operation
P2	Fault on Main Bus
P3	Fault on Line 1

Table 10: Places of the Single Bus with Tie-breaker Configuration PN

Transition	Description
t1	Fault on Main Bus
t2	R1 trigger correctly
t3	R1 failure
t4	Restorative

Table 11: Transitions of the Single Bus with Tie-breaker Configuration PN

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Bus B
P4	Fault on Bus A

Table 12: Places of the Single Bus with Tie-breaker Configuration PN

respectively. After simulate the PN presented in Fig. 21, the fault leads a cascade event on Line 1 the 0.26% of the cases.

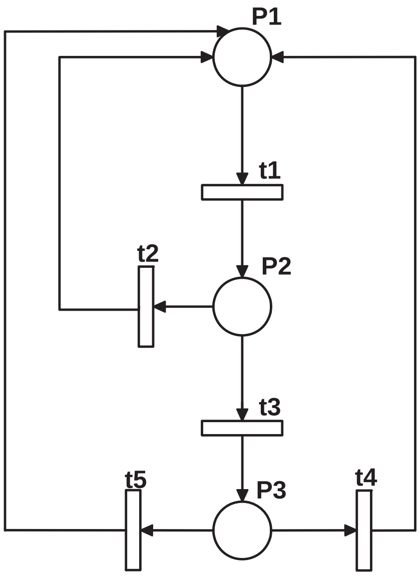

Figure 21: PN for ingle buses connected with bus tie-breaker configuration, Fault on Line 4

3.2.3 Main and transfer Buses Substation

3.2.3.1 Fault on Main-Bus

Fig. 22 presents the Petri Net for the Fault on Main-Bus in the Main and transfer Buses Substation configuration. Tables 14 and 15 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 22, the fault leads a cascade event on Line 1 the 5.0% of the cases.

Transition	Description
t1	Fault on Line 4
t2	R4 trigger correctly
t3	R4 failure
t4	Tie breaker trigger correctly
t5	Tie breaker failure
t6	R1 trigger correctly
t7	R1 failure

Table 13: Transitions of the Single Bus with Tie-breaker Configuration PN

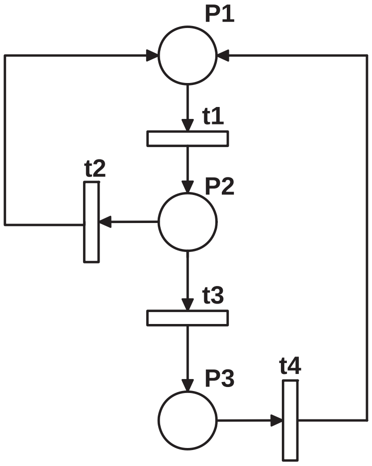

Figure 22: PN for Main and transfer Buses Substation, Fault on Bus

Place	Description
P1	Normal operation
P2	Fault on Main Bus
P3	Fault on Line 1

Table 14: Places of the Main and Transfer Bus Configuration PN

Transition	Description
t1	Fault on Main Bus
t2	R1 trigger correctly
t3	R1 failure
t4	Restorative

Table 15: Transitions of the Main and Transfer Bus Configuration PN

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Main Bus

Table 16: Places of the Main and Transfer Bus Configuration PN

Transition	Description
t1	Fault on Line 4
t2	R4 trigger correctly
t3	R4 failure
t4	R1 trigger correctly
t5	R1 failure

Table 17: Transitions of the Main and Transfer Bus Configuration PN

3.2.3.2 Fault on Line

Fig. 23 presents the Petri Net for the Fault on Main-Bus in the Main and transfer Buses Substation configuration. Tables 16 and 17 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 22, the fault leads a cascade event on Line 1 the 0.26% of the cases.

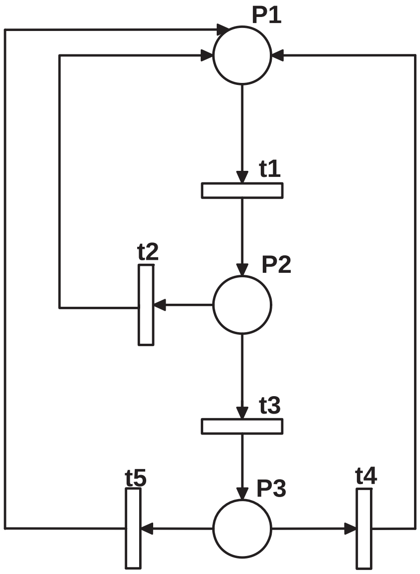

Figure 23: PN for Main and transfer Buses Substation, Fault on Line

Place	Description
P1	Normal operation
P2	Fault on Bus 1
P3	Fault on Line 1

Table 18: Places of the Single Breaker - Double Bus Configuration PN

Transition	Description
t1	Fault on bus 1
t2	R1 trigger correctly
t3	R1 failure
t4	Restorative

Table 19: Transitions of the Single Breaker - Double Bus Configuration PN

3.2.4 Single Breaker - Double Bus Substation

3.2.4.1 Fault on Bus 1

Fig. 24 presents the Petri Net for the Fault on Bus 1 in the Single Breaker - Double Bus Substation configuration. Tables 18 and 19 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 24, the fault leads a cascade event on Line 1 the 5.0% of the cases.

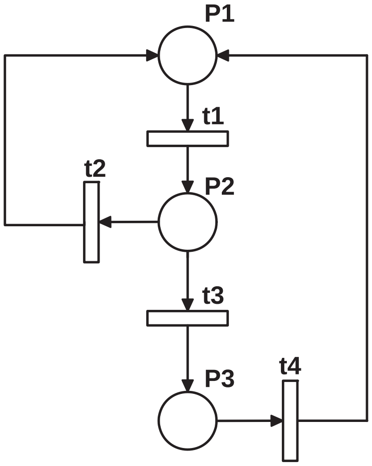

Figure 24: PN for Single Breaker - Double Bus Substation, Fault on Bus 1

3.2.4.2 Fault on Bus 2

Fig. 25 presents the Petri Net for the Fault on Bus 2 in the Single Breaker - Double Bus Substation configuration. Tables 20 and 21 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 25, the fault leads a cascade event on Line 1 the 0.26% of the cases.

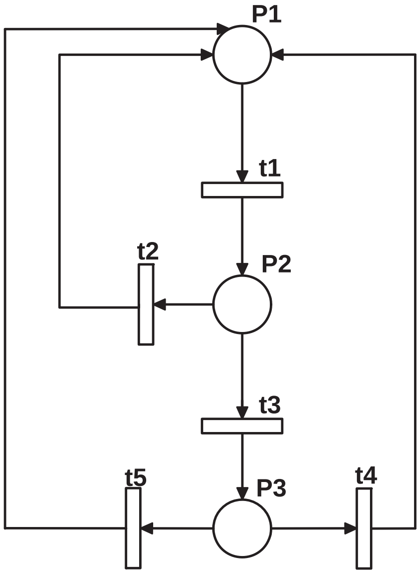

Figure 25: PN for Single Breaker - Double Bus Substation, Fault on Bus 2

Place	**Description**
P1	Normal operation
P2	Fault on Bus 2
P3	Fault on Bus 1

Table 20: Places of the Single Breaker - Double Bus Configuration PN

Transition	**Description**
t1	Fault on bus 2
t2	R5 trigger correctly
t3	R5 failure
t4	R1 trigger correctly
t5	R1 failure

Table 21: Transitions of the Single Breaker - Double Bus Configuration PN

Place	Description
P1	Normal operation
P2	Fault on Line 2
P3	Fault on Line 1

Table 22: Places of the Single Breaker - Double Bus Configuration PN

Transition	Description
t1	Fault on Line 2
t2	R2 trigger correctly
t3	R2 failure
t4	R1 trigger correctly
t5	R1 failure

Table 23: Transitions of the Single Breaker - Double Bus Configuration PN

3.2.4.3 Fault on Line 2

Fig. 26 presents the Petri Net for the Fault on Line 2 in the Single Breaker - Double Bus Substation configuration. Tables 22 and 23 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 26, the fault leads a cascade event on Line 1 the 0.26% of the cases.

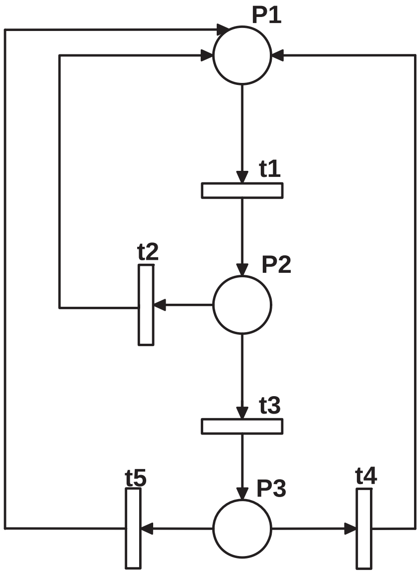

Figure 26: PN for Single Breaker - Double Bus Substation, Fault on Line 2

3.2.4.4 Fault on Line 4

Fig. 27 presents the Petri Net for the Fault on Line 4 in the Single Breaker - Double Bus Substation configuration. Tables 24 and 25 show the places and transitions of the PN,

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Bus 2
P4	Fault on Bus 1

Table 24: Places of the Single Breaker - Double Bus Configuration PN

respectively. After simulate the PN presented in Fig. 27, the fault leads a cascade event on Line 1 the 0.02% of the cases.

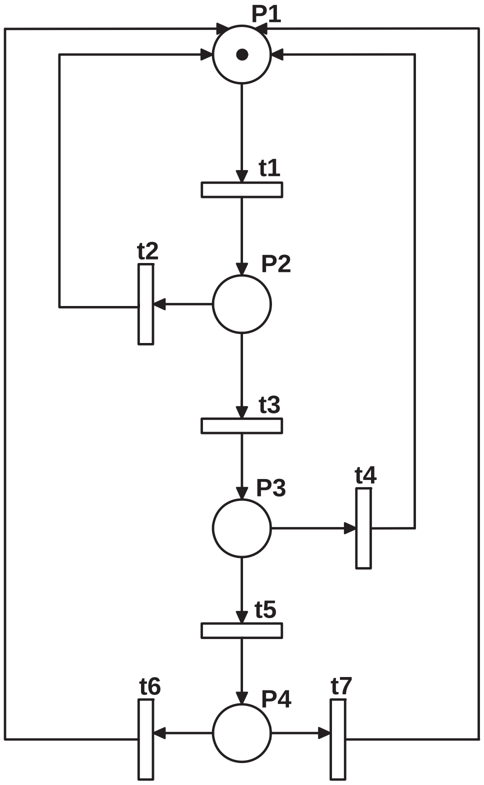

Figure 27: PN for Single Breaker - Double Bus Substation, Fault on Line 4

3.2.5 Ring Bus Substation

3.2.5.1 Fault on Line 2

Fig. 28 presents the Petri Net for the Fault on Line 2 in the Ring Bus Substation configuration. Tables 26 and 27 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 28, the fault leads a cascade event on Line 1 the 5.02% of the cases.

Transition	Description
t1	Fault on Line 4
t2	R4 trigger correctly
t3	R4 failure
t4	R5 trigger correctly
t5	R5 failure
t6	R1 trigger correctly
t7	R1 failure

Table 25: Transitions of the Single Breaker - Double Bus Configuration PN

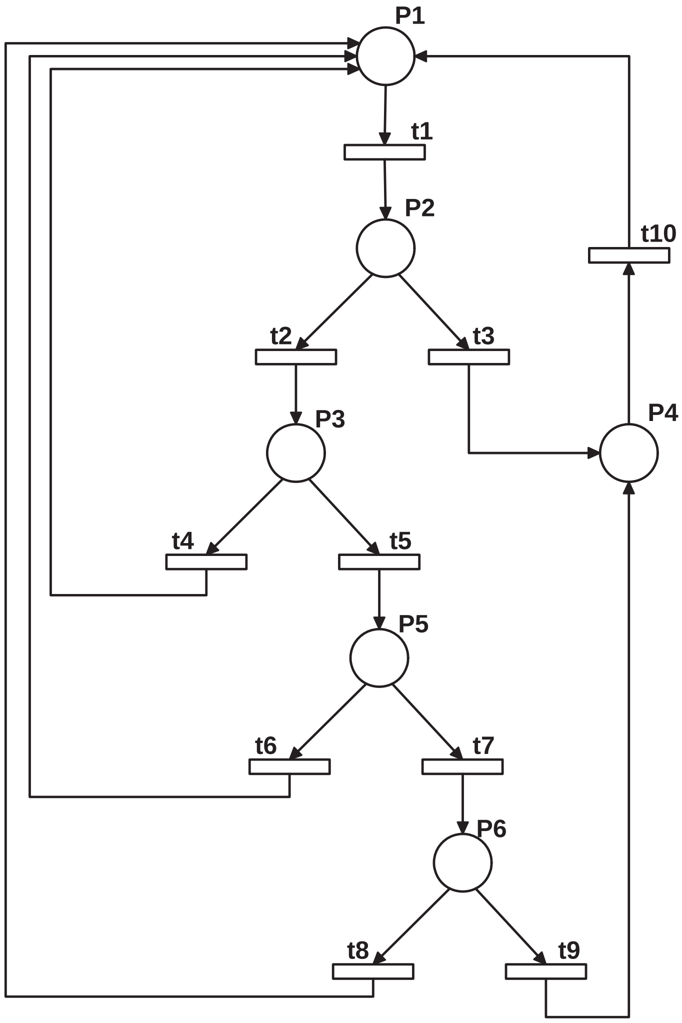

Figure 28: PN for Ring Bus Substation, Fault on Line 2

Place	Description
P1	Normal operation
P2	Fault on Line 2
P3	Fault on Line 2
P4	Fault on Line 1
P5	Fault on Line 3
P6	Fault on Line 4

Table 26: Places of the Ring Bus Configuration PN

Transition	Description
t1	Fault on Line 2
t2	R2 trigger correctly
t3	R2 failure
t4	R3 trigger correctly
t5	R3 failure
t6	R4 trigger correctly
t7	R5 failure
t8	R1 trigger correctly
t9	R1 failure
t10	Restorative

Table 27: Transitions of the Ring Bus Configuration PN

3.2.5.2 Fault on Line 3

Fig. 29 presents the Petri Net for the Fault on Line 3 in the Ring Bus Substation configuration. Tables 28 and 29 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 29, the fault leads a cascade event on Line 1 the 0.52% of the cases.

Place	Description
P1	Normal operation
P2	Fault on Line 3
P3	Fault on Line 2
P4	Fault on Line 1
P5	Fault on Line 4
P6	Fault on Line 2 and 4
P7	Fault on Line 7

Table 28: Places of the Ring Bus Configuration PN

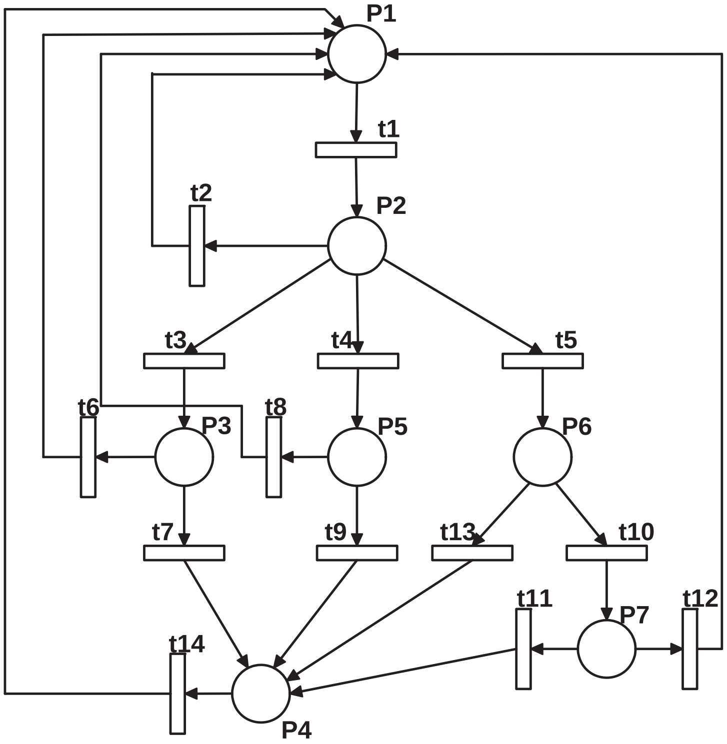

Figure 29: PN for Ring Bus Substation, Fault on Line 3

Transition	Description
t1	Fault on Line 3
t2	R3 and R4 trigger correctly
t3	R3 failure and R4 trigger correctly
t4	R4 failure and R3 trigger correctly
t5	R3 and R4 failure
t6	R2 trigger correctly
t7	R2 failure
t8	R1 trigger correctly
t9	R1 failure
t10	R1 trigger correctly
t11	R2 failure
t12	R2 trigger correctly
t13	R1 failure

Table 29: Transitions of the Ring Bus Configuration PN

Place	Description
P1	Normal operation
P2	Fault on Bus A
P3	Fault on Bus A
P4	Fault on Line 1
P5	Fault on Line 3
P6	Fault on Line 4
P7	Fault on Bus B
P8	Fault on Line 2

Table 30: Places of the Breaker-and-a-half Configuration PN

Transition	Description
t1	Fault on Bus A
t2	R1 trigger correctly
t3	R1 failure
t4	R3 trigger correctly
t5	R3 failure
t6	R6 trigger correctly
t7	R6 failure
t8	R4 trigger correctly
t9	R4 failure
t10	R2 trigger correctly
t11	R2 failure
t12	R5 trigger correctly
t13	R5 failure
t14	Restorative

Table 31: Transitions of the Breaker-and-a-half Configuration PN

3.2.6 Breaker-and-a-half bus Substation

3.2.6.1 Fault on Bus A

Fig. 30 presents the Petri Net for the Fault on Bus A in the Breaker-and-a-half bus Substation configuration. Tables 30 and 31 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 30, the fault leads a cascade event on Line 1 the 5.0% of the cases.

3.2.6.2 Fault on Bus B

Fig. 31 presents the Petri Net for the Fault on Bus B in the Breaker-and-a-half bus Substation configuration. Tables 32 and 33 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 31, the fault leads a cascade event on Line 1 the 0.26% of the cases.

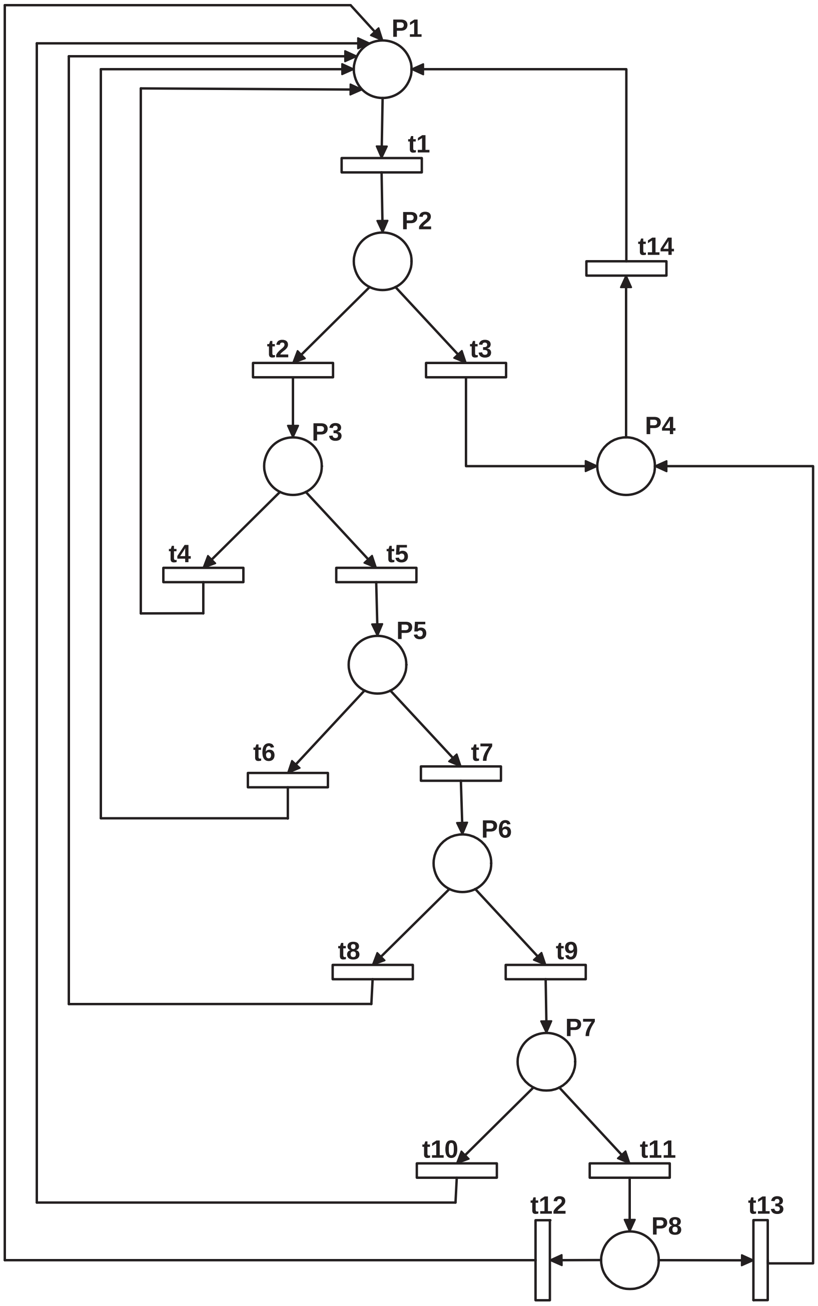

Figure 30: PN for Breaker-and-a-half bus Substation, Fault on Bus A

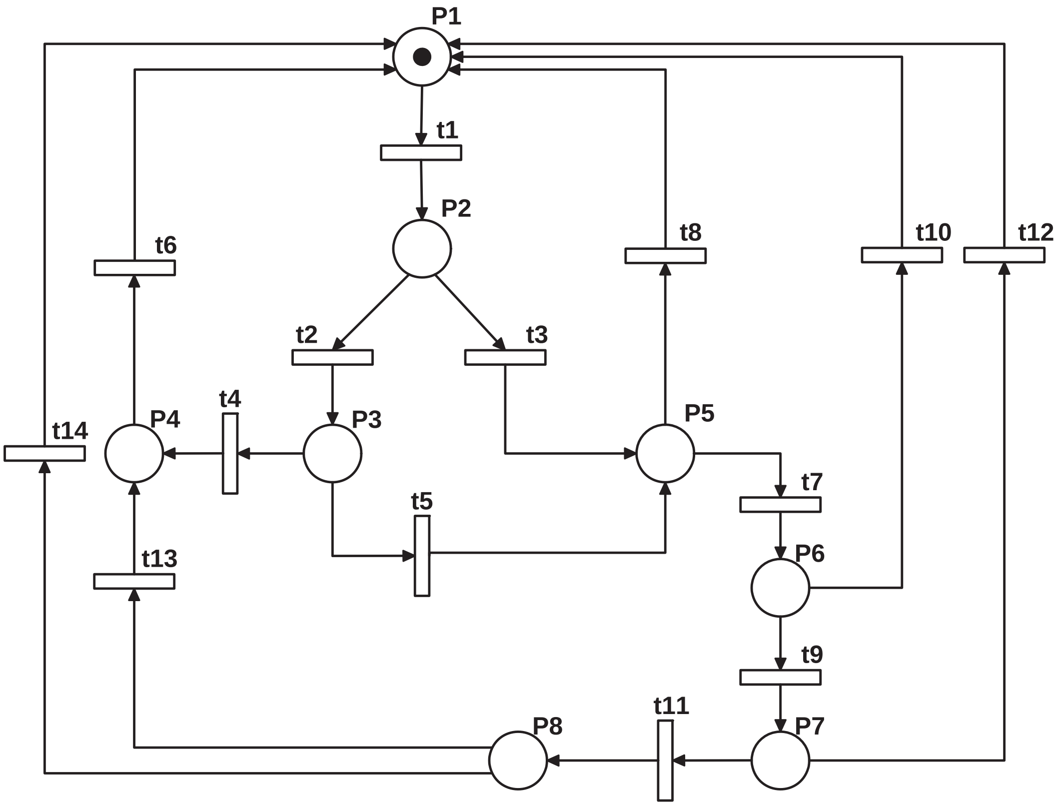

Figure 31: PN for Breaker-and-a-half bus Substation, Fault on Bus B

Place	Description
P1	Normal operation
P2	Fault on Bus B
P3	Fault on Line 2
P4	Fault on Line 1
P5	Fault on Bus B
P6	Fault on Line 4
P7	Fault on Line 3
P8	Fault on Bus A

Table 32: Places of the Breaker-and-a-half Configuration PN

Transition	Description
t1	Fault on Bus B
t2	R2 failure
t3	R2 trigger correctly
t4	R5 failure
t5	R5 trigger correctly
t6	Restorative
t7	R4 failure
t8	R4 trigger correctly
t9	R4 failure
t10	R4 trigger correctly
t11	R4 failure
t12	R4 trigger correctly
t13	R4 failure
t14	R4 trigger correctly

Table 33: Transitions of the Breaker-and-a-half Configuration PN

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Bus B
P4	Fault on Line 1
P5	Fault on Line 4
P6	Fault on Line 2
P7	Fault on Line 3
P8	Fault on Bus A

Table 34: Places of the Breaker-and-a-half Configuration PN

3.2.6.3 Fault on Line 4

Fig. 32 presents the Petri Net for the Fault on Line 4 in the Breaker-and-a-half bus Substation configuration. Tables 34 and 35 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 32, the fault leads a cascade event on Line 1 the 0.04% of the cases.

3.2.7 Double breaker - Double bus Substation

3.2.7.1 Fault on Bus

Fig. 33 presents the Petri Net for the Fault on Bus in the Double breaker - Double bus Substation configuration. Tables 36 and 37 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 33, the fault leads a cascade event on Line 1 the 5.04% of the cases.

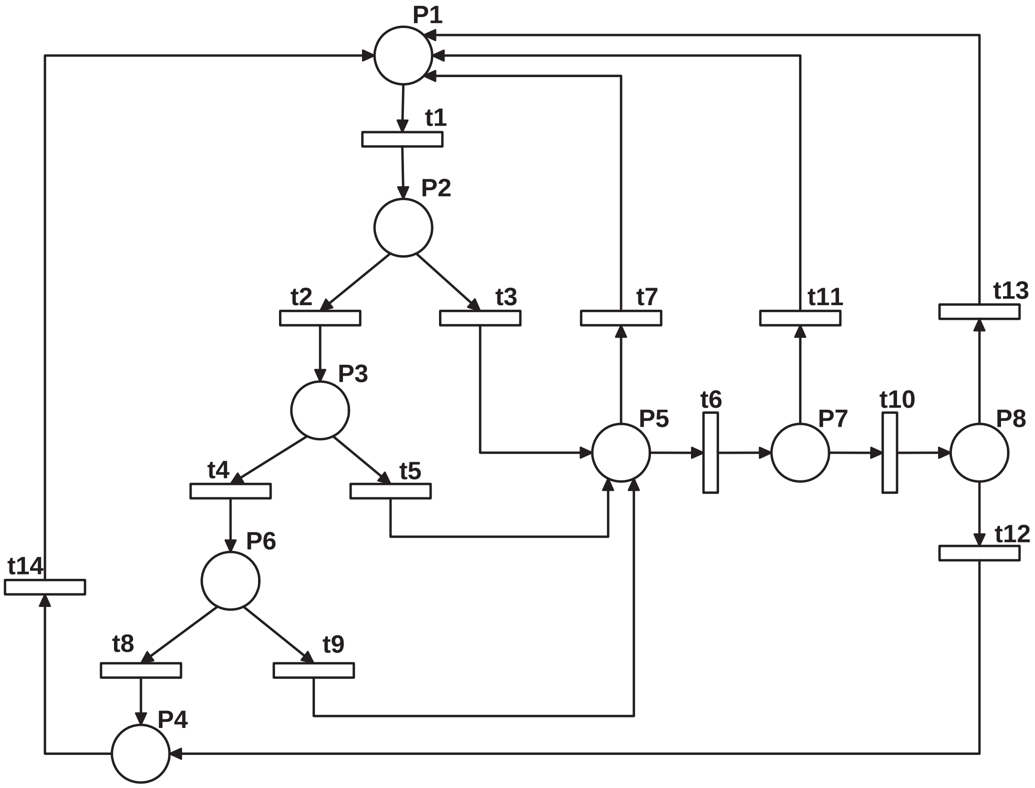

Figure 32: PN for Breaker-and-a-half bus Substation, Fault on Line 4

Transition	Description
t1	Fault on Line 4
t2	R4 failure
t3	R4 trigger correctly
t4	R2 failure
t5	R2 trigger correctly
t6	R6 failure
t7	R6 trigger correctly
t8	R5 failure
t9	R5 trigger correctly
t10	R3 failure
t11	R3 trigger correctly
t12	R1 failure
t13	R1 trigger correctly
t14	Restorative

Table 35: Transitions of the Breaker-and-a-half Configuration PN

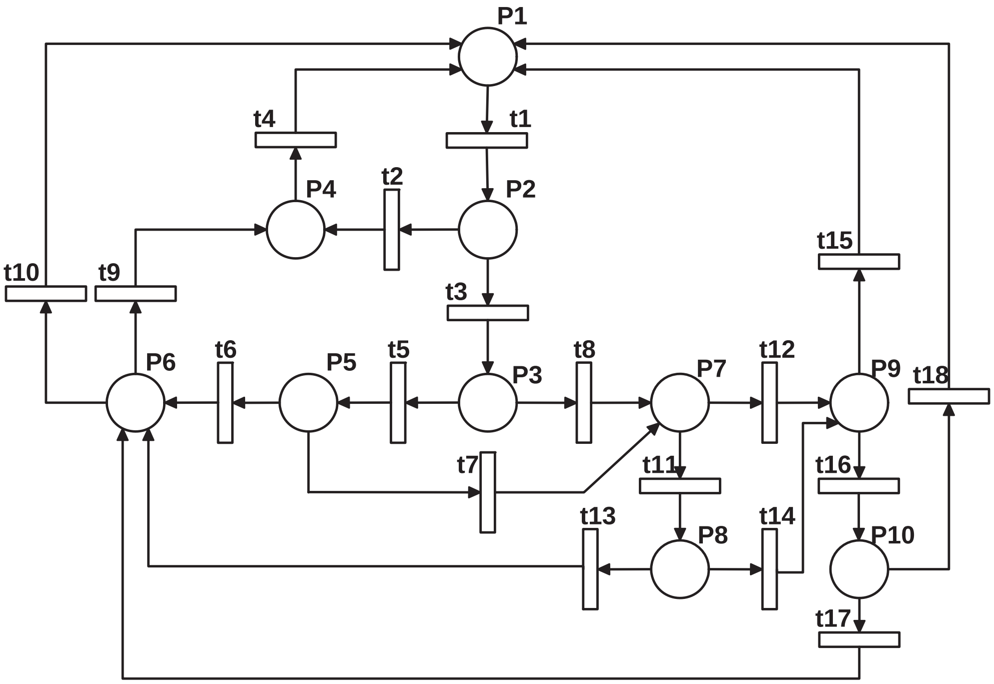

Figure 33: PN for Double breaker - Double bus Substation, Fault on Bus

Place	Description
P1	Normal operation
P2	Fault on Bus 1
P3	Fault on Bus 1
P4	Fault on Line 1
P5	Fault on Line 2
P6	Fault on Bus 2
P7	Fault on Bus 1
P8	Fault on Line 3
P9	Fault on Bus 1
P10	Fault on Line 4

Table 36: Places of the Double breaker - Double bus Configuration PN

Transition	Description
t1	Fault on Bus 1
t2	R1 failure
t3	R1 trigger correctly
t4	Restorative
t5	R3 failure
t6	R6 failure
t7	R4 trigger correctly
t8	R3 trigger correctly
t9	R2 failure
t10	R2 trigger correctly
t11	R5 failure
t12	R5 trigger correctly
t13	R6 failure
t14	R6 trigger correctly
t15	R7 trigger correctly
t16	R7 failure
t17	R8 failure
t18	R8 trigger correctly

Table 37: Transitions of the Double breaker - Double bus Configuration PN

3.2.7.2 Fault on Line

Fig. 34 presents the Petri Net for the Fault on Line in the Double breaker - Double bus Substation configuration. Tables 38 and 39 show the places and transitions of the PN, respectively. After simulate the PN presented in Fig. 34, the fault leads a cascade event on Line 1 the 0.51% of the cases.

3.3 Summary of Security Indexes Assessed

Table 40 presents the security indexes assessed for the seven substation configurations. It can be seen that it is incorrect to assume that all substations have the same failure probability. Furthermore, each substation has different failure probabilities regarding to the sort of analysis. On the other hand, the most secure configurations have more protective systems that can lead the system to a catastrophic event if an inadequate maintenance is performed.

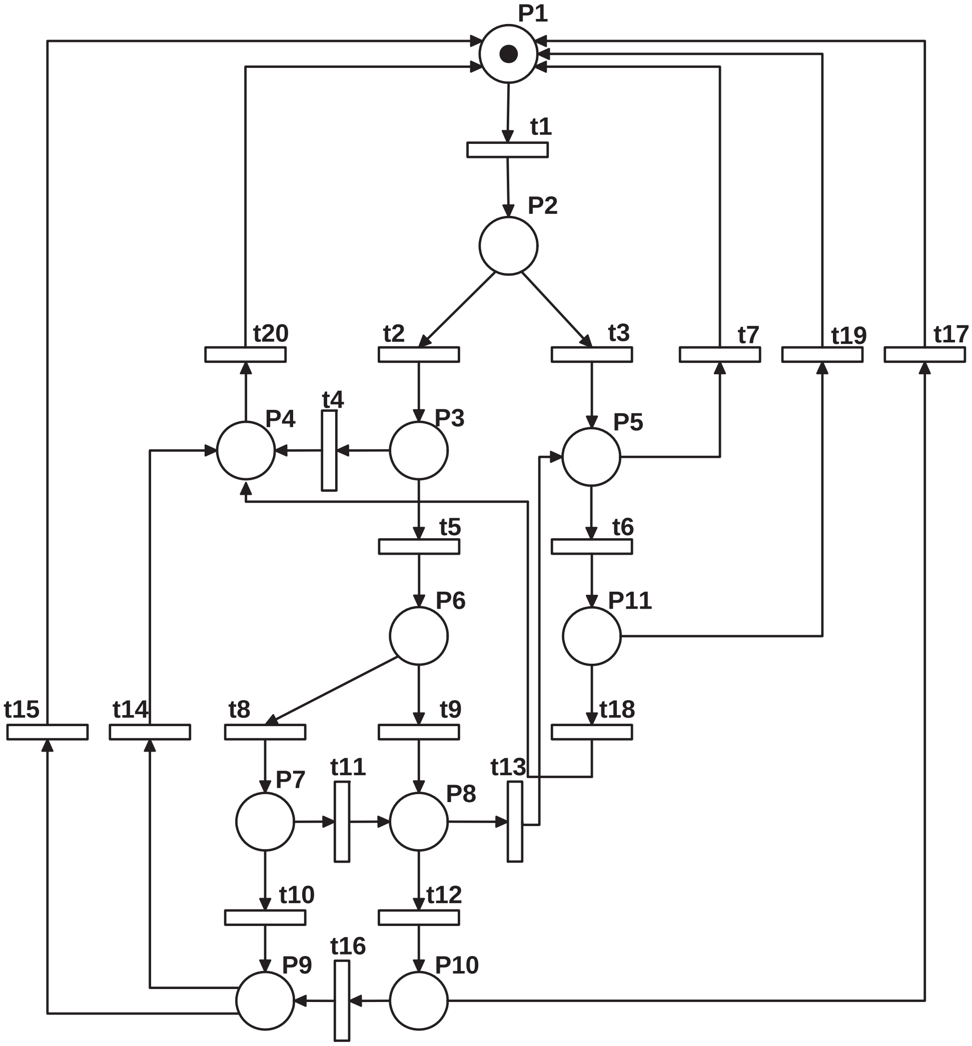

Figure 34: PN for Double breaker - Double bus Substation, Fault on Line

Place	Description
P1	Normal operation
P2	Fault on Line 4
P3	Fault on Bus 2
P4	Fault on Line 1
P5	Fault on Line 4
P6	Fault on Bus 2
P7	Fault on Line 2
P8	Fault on Bus 2
P9	Fault on Bus 1
P10	Fault on Line 3
P11	Fault on Bus 1

Table 38: Places of the Double breaker - Double bus Configuration PN

Transition	Description
t1	Fault on Line 4
t2	R8 failure
t3	R8 trigger correctly
t4	R2 failure
t5	R2 trigger correctly
t6	R7 failure
t7	R7 trigger correctly
t8	R9 failure
t9	R9 trigger correctly
t10	R3 failure
t11	R3 trigger correctly
t12	R6 failure
t13	R6 trigger correctly
t14	R1 failure
t15	R1 trigger correctly
t16	R5 failure
t17	R5 trigger correctly
t18	R1 failure
t19	R1 trigger correctly
t20	Restorative

Table 39: Transitions of the Double breaker - Double bus Configuration PN

Configuration	Bus 1 Fault	Bus 2 Fault	Line 2 Fault	Line 4 Fault
Single Bus	0.05	-	-	0.003
Single Bus with Tie-Breaker	0.05	0.003	0.0026	0.0002
Main and Transfer Buses	0.05	-	0.0026	0.0026
Single Breaker-Double Bus	0.05	0.00263	0.0026	0.0002
Ring Bus	-	-	0.0502	0.052
Breaker-and-a-Half bus	0.05	0.0026	0.05	0.0004
Double Breaker - Double Bus	0.0504	0.0504	0.051	0.051

Table 40: Occurrence Probability of a Cascade Event on Line 1

CHAPTER IV

MODELING CASCADE EVENTS WITH PETRI NETS

The second step corresponds to model the connection of substations with different configurations in order to model cascade events. References [33] and [31] suggest the use of High-level Petri Nets in order to model larger Power Systems. However, the software that simulates High-Level Petri Nets with uncertainties does not exist. Thus, this paper proposes the use of building blocks, see Figure 35, which is basically to break up large systems into smaller units that are easier to handle [7]. For instance, if the main goal is to model a system composed by two substations, the problem solution should be to model each substation separately. Then, combine the solutions together and model the complete system.

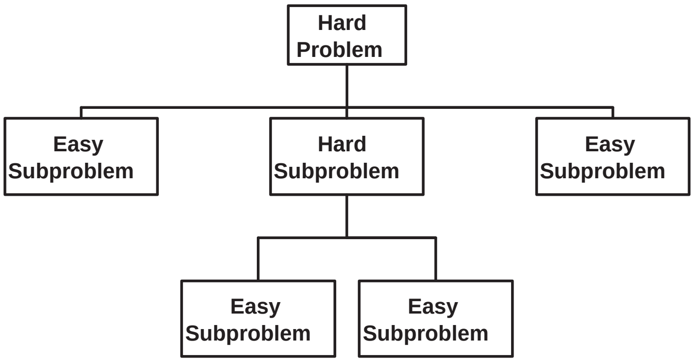

Figure 35: Divide and Conquer Strategy [7]

4.1 Modeling two interconnected substations

4.1.1 Methodology

Figure 37 shows a Petri Net to model the effects of a substation on another substation, those substations are connected as shown in Fig. 36. Transition 1 (t1) fires when there is a fault in the substation 1, e.g. fault on main bus. Transitions 2 and 3 (t2 and t3) are related to the security index for the substation 1 assessed in the first step, that is, the probability of occurrence of a cascade event through the line that connects both substations. Likewise, transitions 4 and 5 (t4 and t5) are related to the security index for the substation 2 assessed in the first step.

Table 41 describes the places of the Petri Net showed above. And Table 42 the transitions.

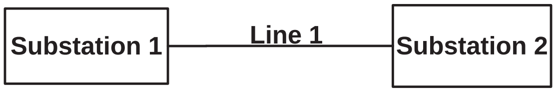

Figure 36: Connection of two substations

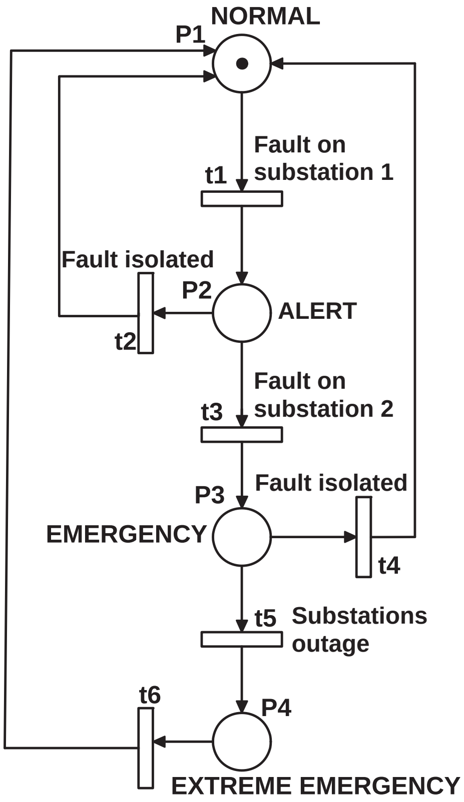

Figure 37: Petri Net for modeling two connected substations

Places	Description
p1	Normal State
p2	Fault on Substation 1
p3	Fault on Substation 2

Table 41: Places of the PN for Two Interconnected Substations

Transitions	Description
t1	Failure on Substation 1
t2	Fault isolated in Substation 1
t3	Fault on Line 1
t4	Fault isolated in Substation 2
t5	System Collapse

Table 42: Transitions of the PN for Two Interconnected Substations

4.1.2 Applications

Table 43 shows the results for two connected substations, according to Fig. 37, taking into account that the first event is a fault on the main bus of the substation. Table 40 shows the probabilities used to evaluate the Petri Network.

Configuration	**Alert**	**Emergency**	**Extreme Emergency**
Single Bus	0.9500	0.0498	0.0002
Single Bus with Tie-Breaker	0.9970	0.0025	0.0002
Main and Transfer Buses	0.9500	0.0498	0.0002
Single Breaker - Double Bus	0.9500	0.0498	0.0002
Ring Bus	-	-	-
Breaker-and-a-Half bus	0.9974	0.0025	0.0001
Double Breaker - Double Bus	0.9496	0.0478	0.0026

Table 43: Operating State Probabilities of Two Connected Substations with the Same Configuration - Fault on Main Bus

On the other hand, Table 44 shows the probabilities of operating states of two connected substations, with fault on a Line as the initiating event.

Configuration	**Alert**	**Emergency**	**Extreme Emergency**
Single Bus with Tie-Breaker	0.9974	0.0024	0.00020
Main and Transfer Buses	0.9974	0.0024	0.00020
Single Breaker - Double Bus	0.9974	0.0024	0.00020
Ring Bus	0.9498	0.0477	0.00025
Breaker-and-a-Half bus	0.9996	0.0003	0.00010
Double Breaker - Double Bus	0.9490	0.0484	0.00026

Table 44: Operating State Probabilities of Two Connected Substations with the Same Configuration - Fault on Line

4.2 Modeling three interconnected substations

4.2.1 Methodology

Figure 38 shows a Petri Net to model the effects of two substations on another substation, those substations are connected as shown in Fig. 39. It is done in the same way than the methodology for two interconnected substations.

4.2.2 Applications

Finally, the main results are summarized in Table 45 taking as an initiating event a Bus A Fault. And in Table 46 taking as an initiating event a Bus B Fault.

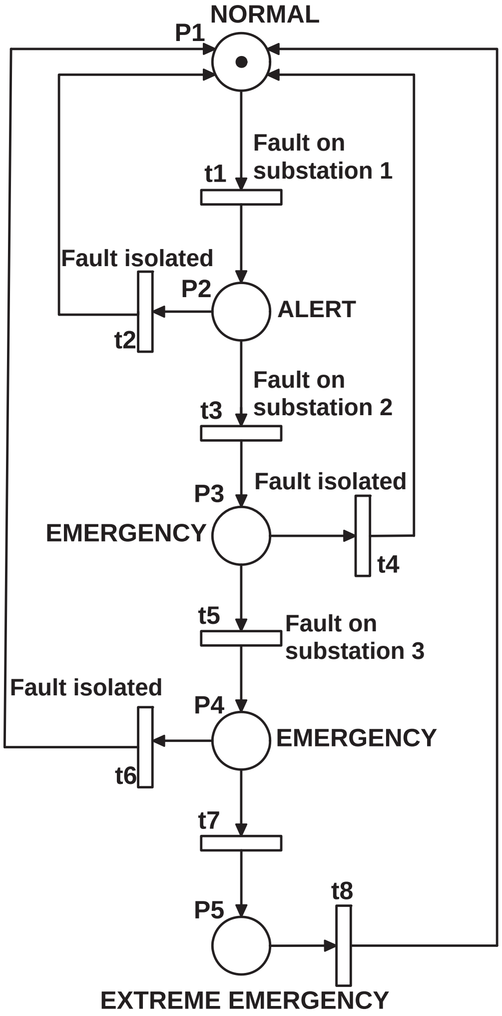

Figure 38: Petri Net for modeling tres connected substations

Figure 39: Connection of three substations

Configuration	Alert	Emergency	Extreme Emergency
Single Bus	0.95000	0.05000	0.00000
Single Bus with Tie-Breaker	0.95000	0.04987	0.00013
Main and Transfer Buses	0.95000	0.04987	0.00013
Single Breaker - Double Bus	0.95000	0.04987	0.00013
Ring Bus	-	-	-
Breaker-and-a-Half bus	0.95000	0.04988	0.00013
Double Breaker - Double Bus	0.94960	0.05027	0.00013

Table 45: Operating State Probabilities of Three Connected Substations with the Same Configuration - Fault on Bus A

Configuration	Alert	Emergency	Extreme Emergency
Single Bus	-	-	-
Single Bus with Tie-Breaker	0.99700	0.00300	0.00000
Main and Transfer Buses	-	-	-
Single Breaker - Double Bus	0.99740	0.00260	0.00000
Ring Bus	-	-	-
Breaker-and-a-Half bus	0.99740	0.00259	0.00001
Double Breaker - Double Bus	0.94960	0.05027	0.00013

Table 46: Operating State Probabilities of Three Connected Substations with the Same Configuration - Fault on Bus B

CHAPTER V

CONCLUSIONS

It has been proposed a methodology for calculating the impact of substations with different configurations on Power Systems. The methodology not only proposes to model the operating sequence of protection devices, but also proposes the modeling of the probability of unreadiness of the protective system. Additionally, it is established the relationship between the operating states of the substations and the Petri Networks.

It has shown that Petri Networks theory is a useful tool for assessing security indexes for Substations. So, the proposed technique allows the security analysis of substations in Power Systems, taking into account hidden failures, unreadiness, and the sequence of operation in protective systems.

The proposed method of building blocks is very effective when it is required to study large Power Systems. Furthermore, the combination of Petri Networks, building blocks, and operating states develop a strong tool to analyze and study the impact of protective systems on the Power System, in terms of adequacy, security, and reliability. This new tool is the main contribution of this paper.

It was demonstrated that the cascade events studies are incomplete without considering different configurations of substations. Additionally, it was demonstrated the importance of selecting the fault to be analyzed, because each fault brings out different probabilities of failure.

As further work, it is proposed to develop graphical software to model High-level Petri Nets with uncertainties. Likewise, it is proposed to apply this methodology to larger Power Systems, e.g. IEEE 118 nodes.

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