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Evaluation of Power System Security with Petri Nets

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1. 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 modelled 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 (Lester & Carlsen, 1978).

According to the NERC 2008 annual report (NERC, 2009), 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 to reinforce 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 (Dong et al, 2003) and (Dobson & McCalley, 2008). However, the main weakness is to forget the impact of a substation fault over neighbors substations, as well as, the uncertainty in the appropriate 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 assess the risk to lead a voltage collapse, taking into account the performance and, furthermore, the unreadiness of the breakers (Anderson, 1999).

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.

This Chapter provides a comprehensive review of the application of Petri nets in security and reliability analysis of Power Systems, such as, electrical industrial systems, meshed power systems and substations. Additionally, special emphasis is done about modelling and interpretation related to the conventional definition of operating states in power systems, i.e. normal state, alert state, emergency, extreme emergency state, and restorative state.

Some applications of Petri Nets are:

- Modelling of cascade phenomenon after operation of protection devices.
- Computing of possible electrical failures in power system protections.
- Risk evaluation of power system unavailability.

Some particular properties that will be covered include:

- Coverability trees, which help to select the operating state of the system.
- All states can be reached in protection schemes of power systems, which represent the liveness of the system. Additionally, in power systems there are no deadlocks, which allow using Petri Networks in order to simulate the behaviour of the system.
- Because there is a restoration state in the system, the property of reversibility is applied.

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.

2. General Overview of Power System Security

Security is defined as the ability of the power system to respond to sudden disturbances without supply interruption. Therefore, security analysis must evaluate non-appropriate response of the system, unnecessary operation of any device (such as protection devices) and/or bad operation of some subsystems when a sudden disturbance occurs. Any of these events affect the power quality and/or the reliability of the electrical system and, consequently, the electrical infrastructure and the associated productive industrial processes lead to a risky scenario.

Operating states of power systems were proposed in (Lester & Carlsen, 1978). 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 Fig. 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 is 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 corrective actions should be carried out 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. 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.

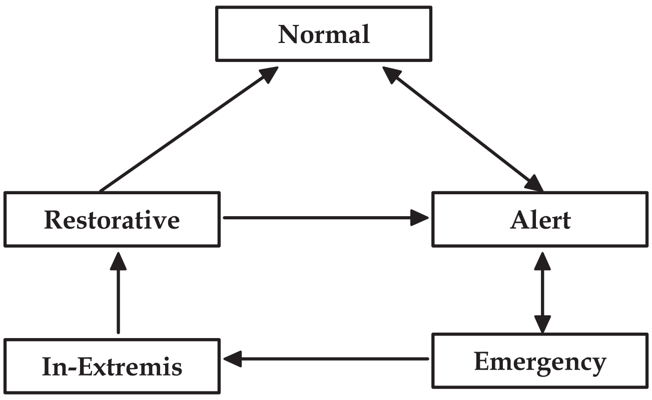

Fig. 1. Operating States of Power Systems

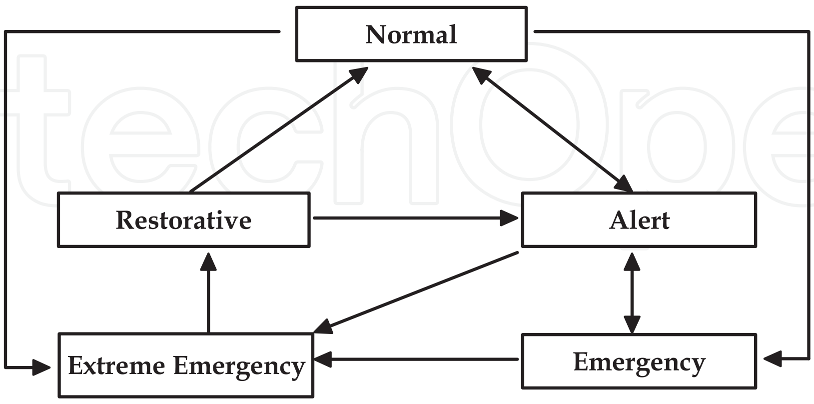

Fig. 2. Improved Operating States of Power Systems

However, the analysis shown above was improved (EPRI, 1987) and (Kundur, 1994). Basically, they added new transitions between the different states. Thus, one of the most complete diagrams is found in (Billinton et al., 1997), which associates the different states as shown in Fig. 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.

3. Petri Net Modelling

A Petri Network is a graphical and mathematical tool to model synchronization process, asynchronous events, sequential operations, concurrent operations, conflicts and resources management (Wang, 1998). PN models can be readily used to describe the system behavior by means of causal relationships between conditions and events in a sequential way. For that reason, PN's are very useful for the analysis of various industrial processes such as production facilities, modeling of electrical systems, and computational systems.

The main components to define the operating states of the Power Systems according Fig. 2, which are taken into account for the formulation of the PN, are the protective devices, such as breakers. So the main events used in the PN formulation are: short circuits, interruption of energy supply, and power quality problems.

Thus, 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 (Jenkins & Khincha, 2006).

As 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. Therefore Petri Networks allows to study power systems, considering unreadiness probabilities and operating states of protections.

Then, the security assessment consists in the computation of the probability of those operating states when a fault occurs in the Power System. Hence, the security assessment methodology using PN is as follow, according to Fig. 3:

1. Definition of the event to be analyzed. It consists in selecting the initiating event. Such event could be short circuits and component outages.
2. System definition: Identification of protective devices such as circuit breakers and relays, including protection zones.
3. Study of possible failures: Main failures are selected in order to simulate their effects on the system. All possible operative states for each device and event are established.
4. Create Petri Net structure. For instance, for each fault in a Power System the PN model is built according to Fig. 4.
5. Assign an operating state for each place in the Petri Net. Fig. 4 shows that a place corresponds to alert state, another place to emergency state and the last one corresponds to extreme emergency state. This step might be done for each place of the PN.
6. Simulation and validation of the Petri Net model, in the Petri Net toolbox V 2.3. (Matcovschi, 2005). This software allows also to study certain properties of the Petri

Net that gives important information about the PN, some of the properties are: liveness, reachability, among others.

7. Generation of the Coverability graph and identification of the operating state of the system.
8. Security index assessment. After simulating the PN, we know how many times the tokens passed through each place, which allows to compute the occurrence probability of each operating state.

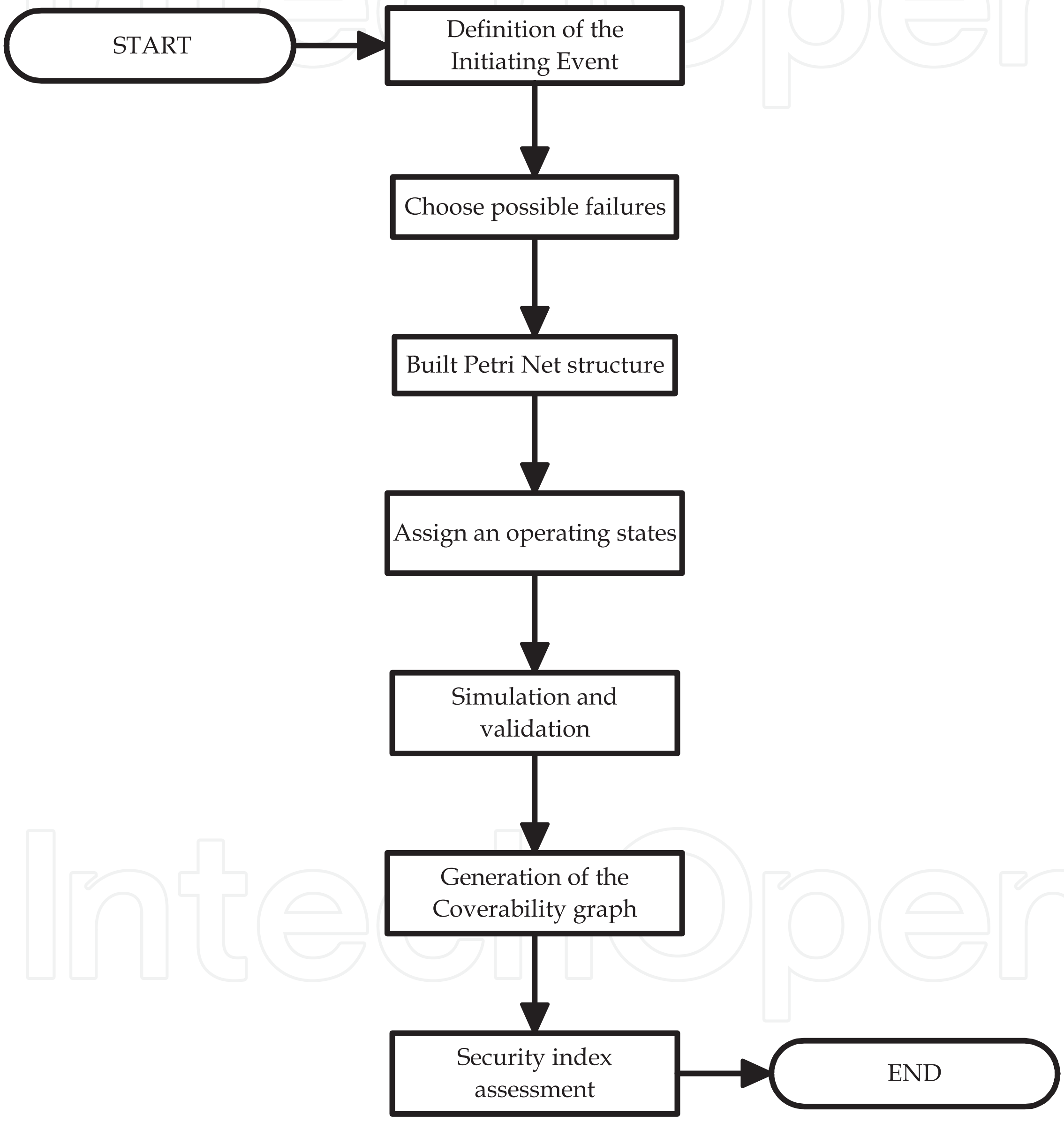

Fig. 3. Security assessment methodology

In order to apply the new methodology for modeling protection sequences with Petri Nets, Fig. 5 presents a power system with 2 buses. Considering two possible failures with the same probability of occurrence, the first one is located close to bus L, and the second one close to bus M. The Petri Net for this system is presented in Fig. 6. As well, places and transitions descriptions are in Table 1 and Table 2.

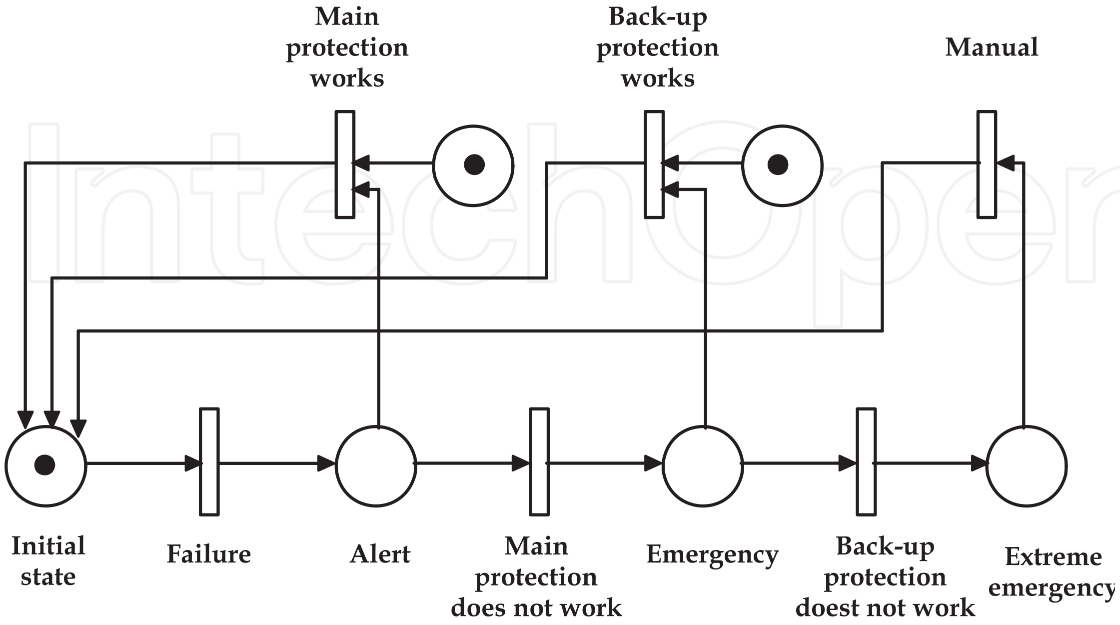

Fig. 4. Proposed Methodology for PN Models of Protection Systems (Sánchez et al. 2008)

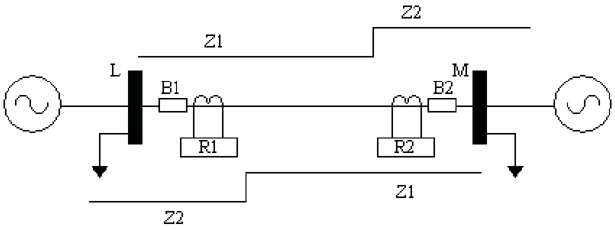

Fig. 5. Two Buses System

Place	Description
p1	Initial state
p2	Fault close to bus L state
p3	Availability of main protection
p4	Isolation of fault by main protection
p5	Emergency state
p6	Availability of back-up protection
p7	Isolation of fault by back-up protection
p8	Extreme emergency state
p9	Isolation of fault by manual operation on main protection
p10	Isolation of fault by manual operation on back-up protection
p11	Fault close to bus M state
p12	Isolation of fault by main protection
p13	Emergency state
p14	Isolation of fault by back-up protection

Table 1. Petri Net Places for 2 Buses System

For the 2 buses system, the Petri Net was simulated with PetriNet Toolbox, and the results - using a failure probability of 5%. Because all protections are taken with the same configuration and failure probabilities, it is expected that almost 5% of cases correspond to emergency state.

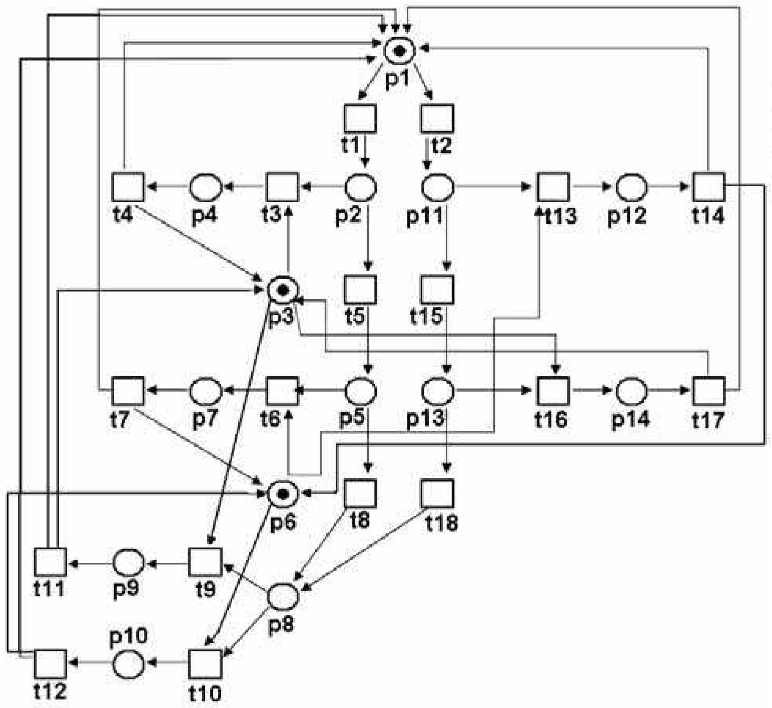

Fig. 6. Petri Net for 2 buses System

Transition	Description
t1	Fault close to bus L
t2	Fault close to bus M
t3	Main protection fired
t4	System restoration
t5	Main protection failed
t6	Back-up protection fired
t7	System restoration
t8	Back-up protection failed
t9	Manual operation
t10	Manual operation
t11	System restoration
t12	System restoration
t13	Main protection fired
t14	System restoration
t15	Main protection failed
t16	Back-up protection fired
t17	System restoration
t18	Back-up protection failed

Table 2. Petri net Transitions for 2 Buses System

4. Applications

4.1 Electrical Industrial Systems (EIS)

4.1.1 Small Radial Systems

The PN modeling is applied to evaluate the sequence operation of a typical protection scheme, as Fig. 7 shows. The system is composed by a local primary protection (B2) and for a remote (backup) protection (B1). The PN model of Fig. 8 shows the transitions scheme between states and specifies the alert, emergency and extreme emergency states. This PN can be used to evaluate the security of the EIS when a fault F1 take place downstream B2.

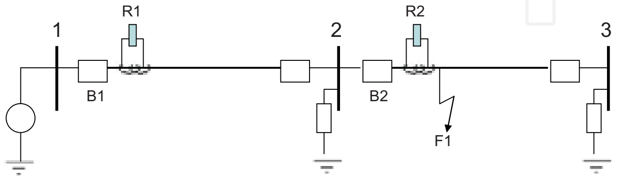

Fig. 7. Typical protection System

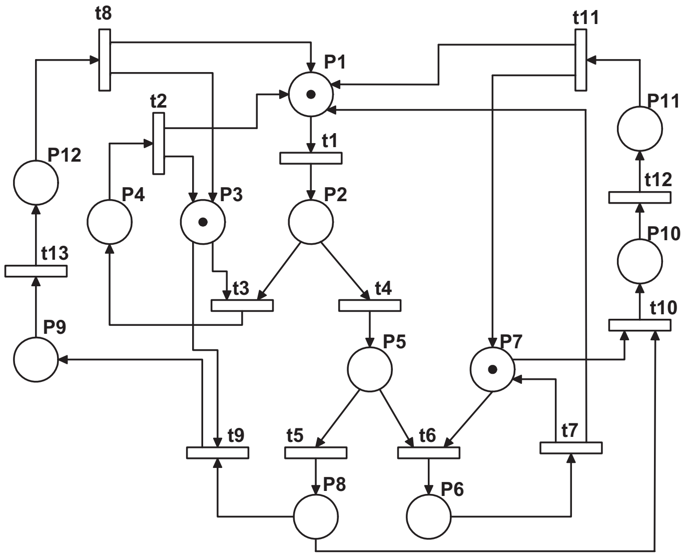

Fig. 8. Petri Net for the EIS basic protection System

The normal state is represented by P1 and the system could reach the P2 state (faulted system) when the transition t1 occurs (short circuit at F). From P2, the system could reach P4 or p5 states by action of conflicting transitions t3 (action of the main protection B1 happens) and t4 (non-action of the main protection B1 happens), respectively. So, in P2 a logical decision is taken between action and non-action of the main protection modeled as a probability (Anderson & Agarwal, 1992) of appropriate operation when it is required.

If the system has reached the p4 state, the transition t2 that represents the restoration of the system, it moves to the P1 state, i.e. to the normal operation state. By contrast, if the system reaches the p5 state (non-operation of the main protection); the same analysis is made for the operation of the backup protection device.

Table 3 lists the places or system states that can be reached by the system when a disturbance occurs; while Table 4 presents the states' transitions. So, from Table 3 and Table

4 a direct relationship is established to the operational states of Fig. 2. Hence, the normal operational state is P1 in the Petri model, alert state is P4, emergency state is P5, extreme emergency state is P6 and restorative state is the addition of P9 and P10.

Place	Description
P1	Normal State
P2	Faulted System between nodes 2 and 3
P3	Main protection available
P4	Alert State - Fault isolated by main protection
P5	Emergency State by non-operation of main relay
P6	Emergency State – Fault isolated by backup protection
P7	Backup protection available
P8	Extreme Emergency State by non-operation of backup relay
P9	Restorative State – system in reparation main→backup
P10	Restorative State – system in reparation backup→main
P11	Restorative State – system repaired
P12	Restorative State – system repaired

Table 3. Places for the Petri Net representation of Basic Protection System

Transition	Description
T1	Fault F1 occurs
T2	Main protection (R2) closes breaker B2
T3	Fault clearance by main protection (R2) (B2 opens)
T4	Main protection (R2) doesn't operate→ B2 is closed
T5	Backup protection (R1) doesn't operate→ B1 is closed
T6	Fault clearance by backup protection (R1)(B1 opens)
T7	Backup protection (R1) closes breaker B1
T8	Manual operation main protection (B2 closes)
T9	Manual operation main protection (B2 opens)
T10	Manual operation main protection (B1 opens)
T11	Manual operation main protection (B1 closes)
T12	Fault in line 2-3 is eliminated
T13	Fault in line 2-3 is eliminated

Table 4. Transitions for the Petri Net Representation of a Basic Protection System

The security indicators are computed by simulations on the Petri Net. Thus, a 10000 probabilistic trials simulation has been made on the PN of Fig. 5 assuming a probability of 95% of appropriate operation of the main and backup protection devices. Thus, for each trial the token is moved through the system states by activation of transitions. The activation of transitions takes into account when a decision between conflicting transitions must be taken. As final result, Fig. 9 shows the conditional probabilities to reach the normal, emergency and extreme emergency states when a fault at F1 happens.

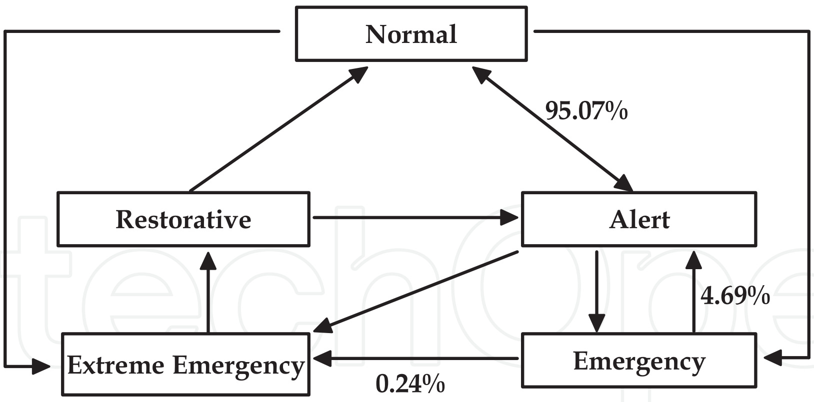

Fig. 9. Probabilities of Operational States Transitions

4.1.2 System IEEE 493

Test System: The electric supply of the IEEE 493 system (Koval et al., 2003) is employed as test system, developed to test methodologies of reliability evaluation in EIS. The IEEE 493 system is a dual utility source system with standby generation in configuration to many mission-critical electric systems, serving both military and commercial facilities. Service transformers are supplied by two independent 15-kV primary distribution feeders. There are four diesel engine generators in the facility, where two of four generators are required to meet the network load demand at all time (Koval et al., 2002).
The complete PN for the supply analysis of the IEEE 493 system is built in two phases: PN for the automatic operation of the main switchgear (generation and utility supply) and the PN for the alimentation of loads from the main switchgear.

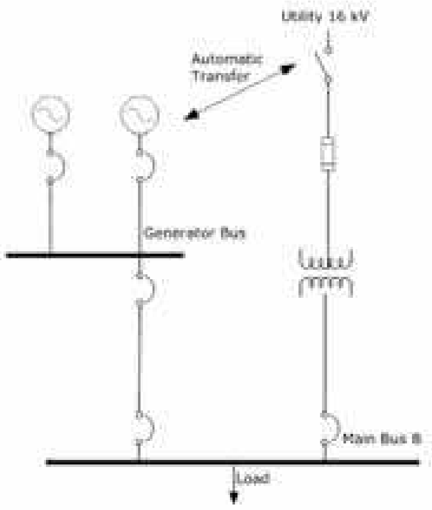

Fig. 10. Automatic Transfer System Scheme IEEE 493 Trest System

Automatic Transfer System: Automatic transfer switches are an integral part of the power generation process, shown in Fig. 10. If the power supply from the utility is interrupted, the transfer switch sends a start signal to the generator and then transfers the load. When the utility power returns, the transfer switch stops the generator and transfers the load. Fig. 11

shows a PN model for automatic transfer system with power utility and generator systems (Ramos et al., 2009).

Table 5 lists the places or system states that can be reached by the system when an outage occurs and Table 6 presents the transitions of the states. So, from Table 5 and Table 6 a direct relationship is established to the operating states of Fig. 12. Hence, the normal operating states are P1 and P8 in the Petri Model, alert state is P3, emergency states are P5 and P11, extreme emergency states are P6, P7, P9 and P10, and restorative states are equivalent to extreme emergency states.

Conflicting transitions are present when: a supply outage is present (T2-T3), the generator is starting (T6-T7), and the generator fails after starting (T8-T10).

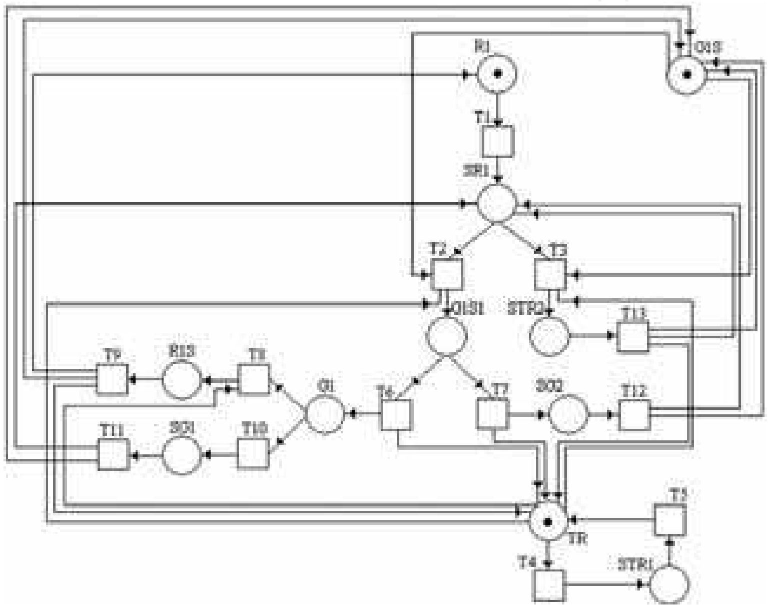

Fig. 11. Petri Net for Transfer System

Fig. 12 shows the conditional probabilities to reach the normal, emergency, and extreme emergency status when an outage happens assuming a probability of 95% of appropriate operation of the generator and transfer switch.

Load System: The load system is composed by a main distribution circuit and two branch circuits, Bus A and Mech Bus A. The main distribution circuit is protected for Main Bus A protection (4000A), the branch circuits are protected for Bus A protection (1600A) and Mech Bus A protection (800A), shown in Fig. 13. Each circuit has primary and secondary protections; e.g. Bus A protection is the primary protection and Main Bus A protection is the back-up protection for the Bus A circuit. Fig. 14 shows the PN for the load system which is similar to the typical protections system with two branch circuits. The conditional probabilities to reach state when a supply outage happens, assuming a probability of 95% of appropriate operation of the protection system of loads are: from alert to normal state 62.17%, from emergency to normal state 35.96%, and from emergency to extreme emergency 1.87%.

Place	Description
P1-R1	Normal State. System on R1
P2-G1S	Generator standby available
P3-SR1	Alert State - Outage R1
P4-TR	Transfer system available
P5-G1S1	Emergency State. G1starting
P6-STR1	Extreme Emergency. Transfer system unavailable
P7-STR2	Extreme Emergency. Transfer system don't work
P8-G1	Normal State. System on G1
P9-SG1	Extreme Emergency. G1 don't start
P10-SG2	Extreme emergency. Fault on G1
P11-R1S	Emergency State. R1 starting

Table 5. Places for the PN Representation of the Transfer System

Transition	Description
T1	Power in R1 is interrupted
T2	Transfer works on demand
T3	Transfer don't work on demand
T4	Transfer out of service. Maintenance
T5, T13	Transfer repaired
T6	G1 starts
T7	G1 don't start
T8	R1 returns
T9	Transfer returns on Normal state
T10	G1 don't work by fault
T11, T12	G1 repaired

Table 6. Transitions for the PN Representation of the Transfer System

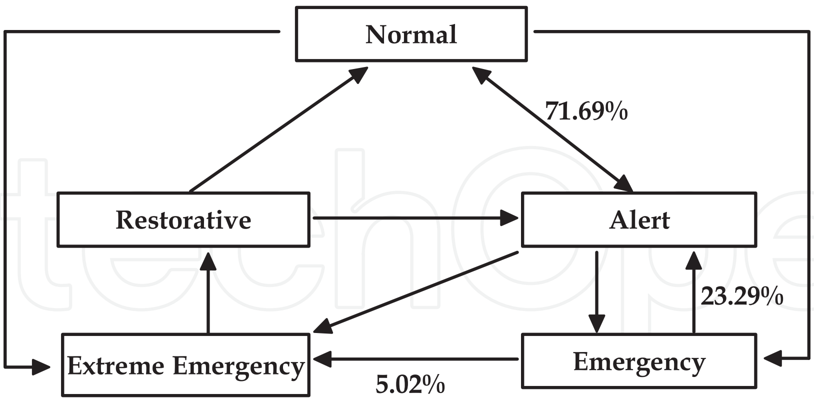

Fig. 12. Probabilities of Operatin States for Transfer System

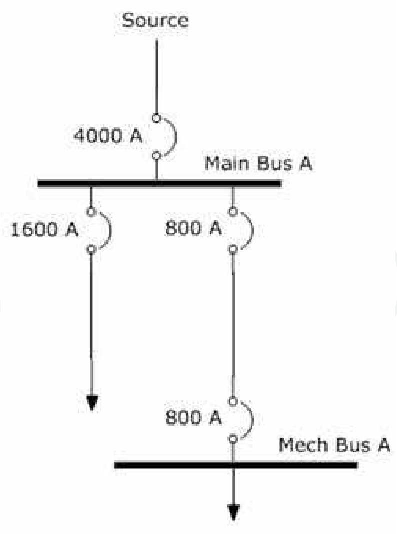

Fig. 13. Load System Scheme IEEE 493 Test Systen

Table 7 lists the places or system states that can be reached by the system when an outage occurs and Table 8 presents the states' transitions. Table 7 and Table 8show the operating states transitions. Hence, the normal operating states are P1 and P8 in the Petri model, alert state is P3, emergency states are P5 and P11, extreme emergency states are P6, P7, P9 and P10, and restorative states are equivalent to extreme emergency states.

Place	Description
P1	Normal State
P2	Faulted System between Main Bus A and Bus A
P3	Faulted System between Main Bus A and Mech Bus A
P4-Emerg	Faulted System between Utility system and Main bus A
	Emergency state by non-operation of Bus A or mesh
	bus relay
P5	Bus A protection available
P6	Alert State - Fault isolated by Bus A protection
P7	Mech Bus A protection available
P8	Alert State - Fault isolated by Mech Bus A protection
P9	Main protection available
P10-extreme	Extreme emergency State by non-operation of main relay
P11	Emergency State–Fault isolated by main protection
P12	Restorative State–system in reparation for Bus A
P13	Restorative State–system in reparation for Main Bus A
P14	Restorative State–system in reparation for Mech Bus A

Table 7. Places for the PN Representation of the Load System

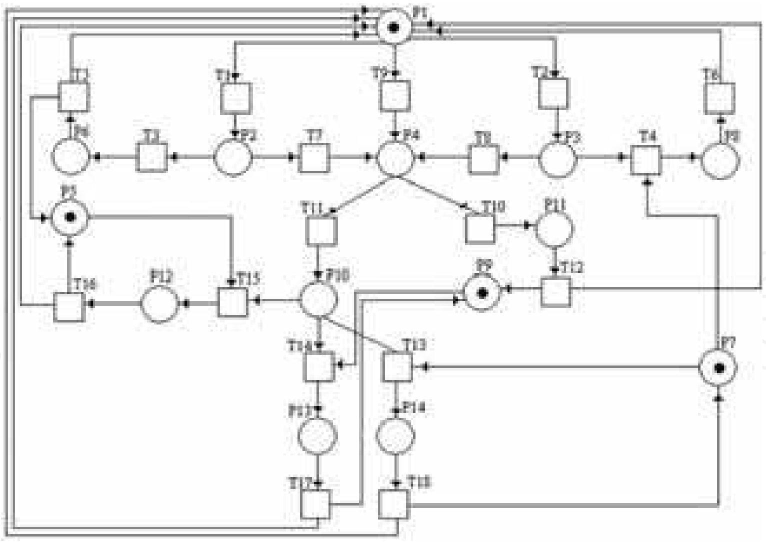

Fig. 14. Petri Net for Load System

Transition	Description
T1	Fault in Bus A occurs
T2	Fault in Mech Bus A occurs
T3	Fault clearance by Bus A protection
T4	Fault clearance by Mech Bus A protection
T5	Bus A protection closes breaker
T6	Mech Bus A protection closes breaker
T7	Bus A protection doesn’t operate
T8	Mech Bus A protection doesn’t operate
T9	Fault in Main Bus A occurs
T10	Fault clearance by Main protection
T11	Main Bus A protection doesn’t operate
T12	Fault clearance by Main Bus A protection
T13	Manual operation Mech Bus A protection
T14	Manual operation Main Bus A protection
T15	Manual operation Bus A protection
T16	Fault between Main Bus A and Bus A is eliminated
T17	Fault between Utility and Main Bus A is eliminated
T18	Fault between Main Bus A and Mech Bus A is eliminated

Table 8. Trasitions for the PN Representation of the Load System

Fig. 15 shows the complete PN for the supply analysis of the IEEE 493 system, which is elaborated from Fig. 11 and Fig. 14 with an appropriate renumbering of these states.

The connection between these PN’s is established by means of modeling and analysis of contingencies and the protection coordination among two subsystems, and the transfer system response. Then, each place is classified as one operating state: normal, alert, emergency, extreme emergency, and restorative. In this way, the simulation computes the probability of occurrence of each place when a fault in the power system occurs, and in consequence, the security indicators are computed. A 10000 probabilistic trials simulation has been made on the PN assuming a probability of 95% of appropriate operation of the main and backup protection devices, and for the automatic transfer between generators.

That number of trials satisfies an error lower than 5% with a 95% of confidence level. Then, for each trial, the token is moved through the system states after transitions fire. The activation of transitions is taken into account when a decision between conflicting transitions must take place. The conditional probabilities to reach the normal, emergency and extreme emergency status are: from alert to normal state 62.17%, from emergency to normal state 35.96%, and from emergency to extreme emergency 1.87%. The system will be in secure states in 87.43% when a fault (short circuit) occurs in the system.

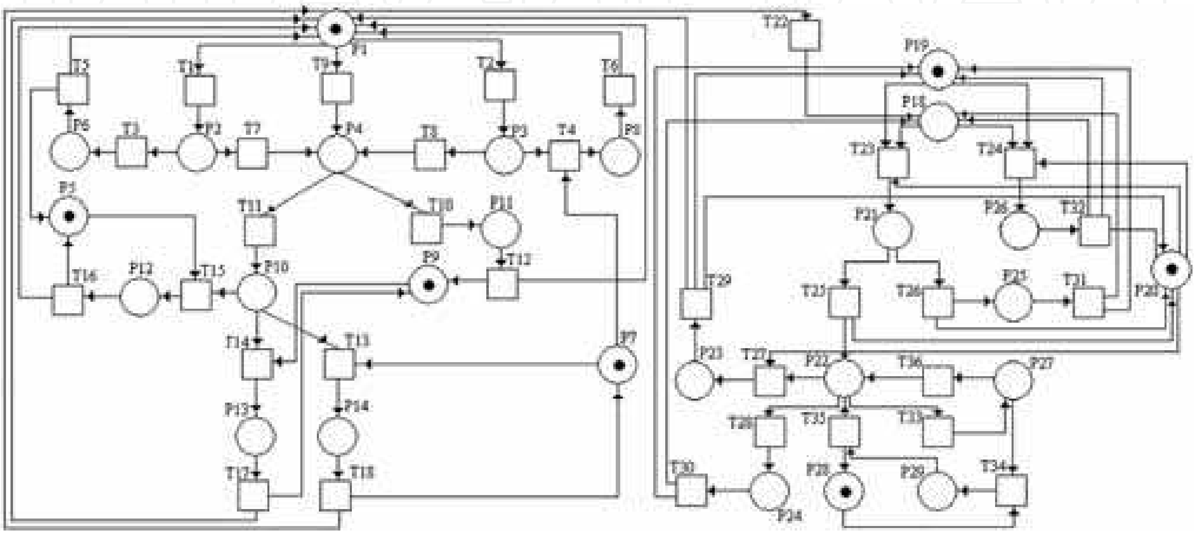

Fig. 15. Petri Net for Total System

4.2 Looped Power Systems

A looped power system with 4 buses, with 8 possible faults, each one at the begin and end of each line. Also, this system has 8 sets of protection. The system is shown in Fig. 16 and the Sub-Petri Net modeled is presented in Fig. 17, which represents a fault in line 1. This model is similar to the other line faults, and all Sub-PN are connected.

After simulating the complete Petri Net, 95.2% of failures were cleared by the main protections and 4.56% of failures were isolated by back-up protections. It was expected that almost 5% of cases correspond to the emergency state, because all protections are taken with the same configuration and failure probabilities.

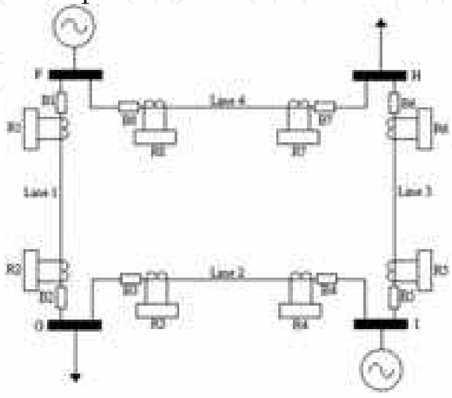

Fig. 16. Four Buses-system

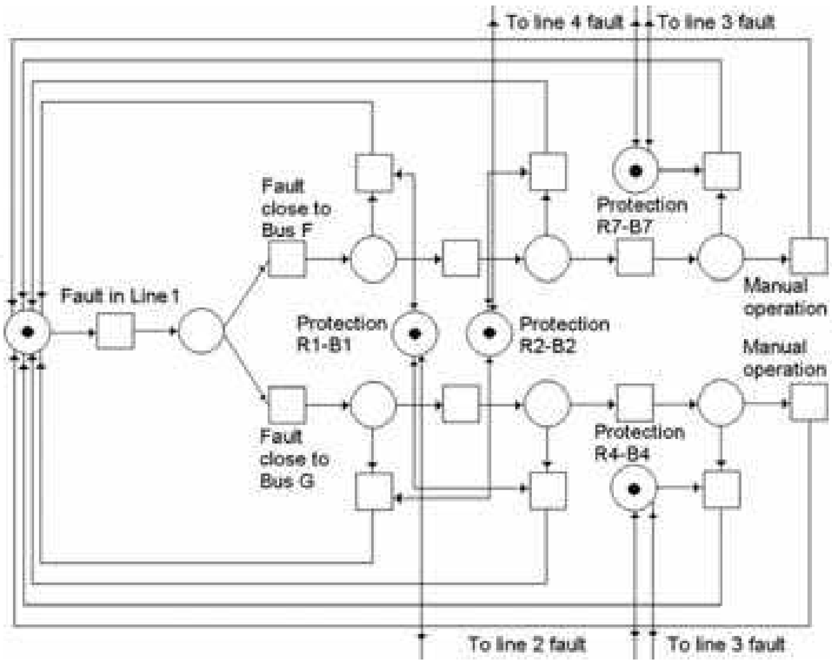

Fig. 17. Sub-Petri net for 4 Buses System

4.3 Substations

Substations have always been modeled as a single bus bar (Caro & Rios, 2008) and (Ramos et al., 2009). Furthermore, all the circuits connected to the substation trigger when a system fault is simulated. Nevertheless, there are many different configurations in substations, e.g. single bus, ring bus and breaker-and-a-half bus (Mc Donald, 2007). 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.

4.3.1 Single Bus

The first configuration studied corresponds to the Single Bus Substation, shown in Fig. 18. In this configuration, the circuits are connected to the Bus through a single switch. The main disadvantage of this configuration is the lack of reliability, security, and flexibility (Mc Donald, 2007). The faults evaluated are: Fault on Bus and Fault on Line 4, and the Line 1 was selected to evaluate the probability of occurrence of a Cascade Event.

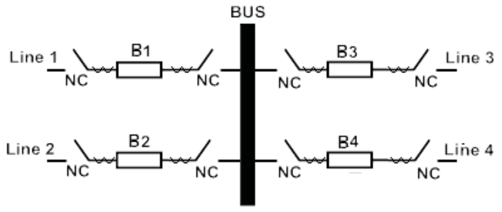

Fig. 18. Single Bus Substation Configuration

Fig. 19 presents the Petri Net for the Fault on Bus in the Single Bus Substation configuration. Table 9 and Table 10 show the places and transitions of the PN, respectively.

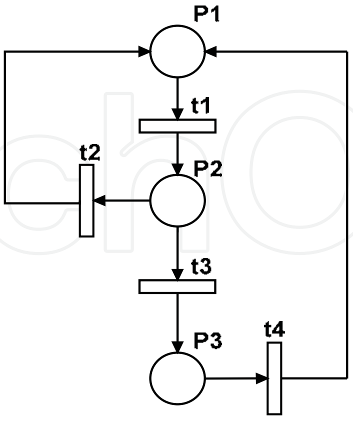

Fig. 19. Petri Net Representation for a Bus Fault on Single Bus Configuration

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

Table 9. Places for a Bus Fault on Single Bus Configuration

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

Table 10. Transitions for a Bus Fault on Single Bus Configuration

After simulate the PN presented in Fig. 19, the fault leads a cascade event on Line 1 the 5% of the cases. It can be seen that because there is only one bus, 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.

4.3.2 Breaker-and-a-half Bus

The breaker-and-a-half bus configuration offers a flexible operation, and high reliability. Also, this configuration allows to isolate any breaker for maintenance without service disruption (Mc Donald, 2007). However, it presents a more complicate relaying, because the center breaker has to act on faults for either of the two circuits . Fig. 20 shows a diagram of this configuration.

The PN for a Line 4 fault in the Breaker-and-a-half bus configuration is shown in Fig. 21. Table 11 and Table 12 show the places and transitions of the PN, respectively.

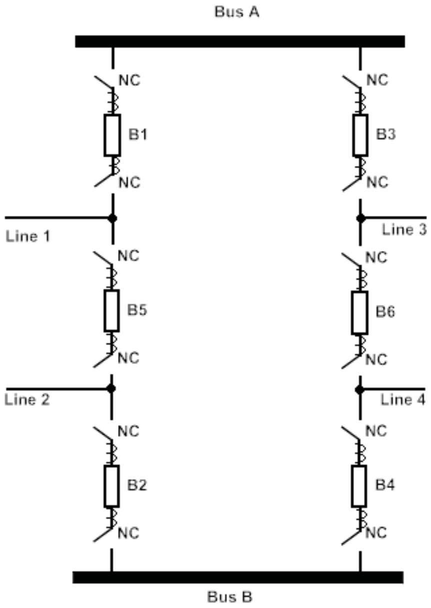

Fig. 20. Breaker-and-a-half Configuration

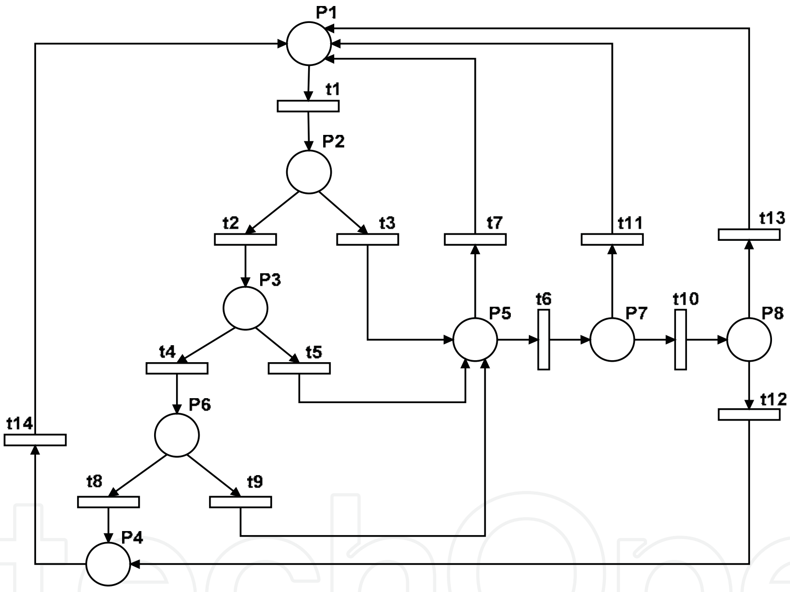

Fig. 21. Petri net Representation for Line 4 Fault on Breaker-and-a-half Configuration

After simulate the PN presented in Fig. 21, the fault leads a cascade event on Line 1 the 0.04% of the cases. According to this result, it is clear that this configuration has a high reliability, as well as high security and adequacy.

4.4 Large Power Systems

For large power Systems, it is proposed the use of building blocks theory, which is basically to break up large systems into smaller units that are easier to handle (Dale et al., 2004) . For instance, if the main goal is to model a system composed by two subsystems, the problem solution should be to model each subsystem separately. Then, combine the solutions together and model the complete system.

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 11. Places for Line 4 Fault on Breaker-and-a-half Bus Configuration

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

Table 12. Transitions for Line 4 Fault on Breaker-and-a-haf Bus Configuration

So, in order to model the connection of substations with different configurations. (Ramos et al., 2009) and (Sánchez et al., 2008) 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, we proposes the use of building blocks, which is basically to break up large systems into smaller units that are easier to handle. 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.

4.4.1 Modelling two interconnected substations

Fig. 22 shows a Petri Net to model the effects of a substation on another substation. 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.

A similar diagram can be obtained for multiple connections and/or multiple substations, according to the size of the system to model.

Table 13 shows the results for two connected substations, according to Fig. 22, taking into account that the first event is a fault on the main bus of the substation. On the other hand, Table 14 shows the probabilities of operating states of two connected substations, with fault on a Line as the initiating event.

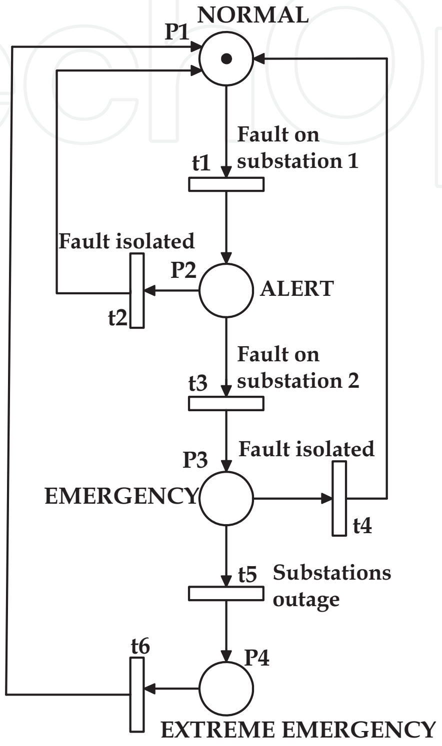

Fig. 22. Petri Net for modeling two connected substations

Configuration	Alert	Emergency	Extreme Emergency
Single Bus with Tie-Breaker	0.9500	0.0498	0.0002
Main and Transfer Buses	0.9970	0.0025	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 13. Operating State Probabilities of Two Connected Substations Fault on Main Bus

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 14. Operating State Probabilities of Two Connected Substations - Fault on Line

5. Conclusions

This chapter has proposed a methodology of security assessment of Power Systems based on Petri Nets Theory. The methodology not only proposes to model the operating sequence of protection devices, but also proposes the modeling of uncertainty in the operation of protection devices using GSPN, and it proposes to measure its impact on the security assessment. Thus, it is proposed the establishment of a relationship between the operating states of Power Systems and the Petri Net models' places, in order to determine the Petri Net Places that model the non-secure operating states.

This chapter has shown that Petri Networks theory is 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.

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 failures probabilities.

The Generalized Stochastic Petri Networks (GSPN) is a rigorous mathematical technique for the electrical systems security analysis that allows the modeling and simulations of system with a large number of states. On the other hand, the modeling capabilities of GSPN allow the inclusion of models of time transitions between states, different to the exponential distributions.

Simulation results on the GSPN of power systems give an easy and intuitive interpretation of the probability of keeping each operating state of the system. Therefore, these state probabilities complement traditional reliability system indicators, assisting to understand the effect of a fault element on system operation.

The numerical results are consistent with expectations, since for all protections it is assumed equal failure probabilities. For this reason, the results would change if there are used different failure probabilities for each protection.

The future application of Petri Nets for assessment of larger Power Systems requires the use of High-level Petri Nets, e.g. Colored Petri Nets. It is proposed as further work, to develop a 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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Petri Nets Applications
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Petri Nets are graphical and mathematical tool used in many different science domains. Their characteristic features are the intuitive graphical modeling language and advanced formal analysis method. The concurrence of performed actions is the natural phenomenon due to which Petri Nets are perceived as mathematical tool for modeling concurrent systems. The nets whose model was extended with the time model can be applied in modeling real-time systems. Petri Nets were introduced in the doctoral dissertation by K.A. Petri, titled "„Kommunikation mit Automaten" and published in 1962 by University of Bonn. During more than 40 years of development of this theory, many different classes were formed and the scope of applications was extended. Depending on particular needs, the net definition was changed and adjusted to the considered problem. The unusual "flexibility" of this theory makes it possible to introduce all these modifications. Owing to varied currently known net classes, it is relatively easy to find a proper class for the specific application. The present monograph shows the whole spectrum of Petri Nets applications, from classic applications (to which the theory is specially dedicated) like computer science and control systems, through fault diagnosis, manufacturing, power systems, traffic systems, transport and down to Web applications. At the same time, the publication describes the diversity of investigations performed with use of Petri Nets in science centers all over the world.

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