Power Systems Security Evaluation Using Petri Nets

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***Abstract*—Misoperation and hidden failures of protections in electric power systems have been recognized as a contributing factor to power system cascading outages and catastrophic events. For that reason, it is important to develop new tools to study the sequence of the operation of protections given a contingency in the system. This paper proposes a methodology for modeling the operating sequences of protections in the IEEE 493 system and a meshed transmission system using generalized stochastic petri nets (GSPNs), contemplating main and back-up protections, and specially how they interact.**

***Index Terms*—Industrial power system reliability, meshed systems, modeling, petri nets (PNs), power transmission protection.**

I. Introduction

ENERGY supply is vitally important for daily life. Nowadays, it is required high levels of security, quality, reliability and availability (SQRA) in the Electrical Industrial Systems (EIS), because EIS are one of the most critical infrastructures of many industries that use sensible electronic loads or major processes based on electricity supply. For this reason, there is an increased interest for developing tools that allow the security evaluation of the EIS and, at the same time, include power quality and reliability criteria for this evaluation [1], [2].

The reliability evaluation of EIS must consider not only the adequacy evaluation of the system, but also the security analysis in order to define the system response to several disturbances [3]. Current reliability techniques model disturbances in a probabilistic way; however, they do not model the stochastic response of the power system [4] and the system is analyzed under steady-state conditions after the disturbances occur [5]. Such techniques are: zone branch [6], cut set [7], go [8] and reliability block diagram [9]. So, using these techniques, it is not possible to define indicators that include the temporal response of the EIS when sudden disturbances occur.

This paper presents a methodology to evaluate the security of the EIS considering the system response to sudden disturbances produced by short circuits and component outages, considering that these failures are critical in power systems [10].

Generalized stochastic petri networks (GSPN) are used to evaluate the EIS's security looking for the operation sequence of protection devices when short circuits or unplanned energy interruptions arise. Reference [11] shows a general overview of using petri net (PN) models for evaluating the reliability of the system when the operation of its components is involved.

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The EIS' PN modeling is based on the operating states of the system [12] and on the unreadiness probability of each protection device [13]. Hence, the PN model allows the computation of probability of each operating state of the system as function of probability of the appropriate operation of protection devices.

The proposed methodology is applied to both the IEEE 493 system [5], taking into account the operation of the main and back-up protections, in order to obtain a quantitative method to assess and measure how catastrophic the failure is, taking into account the possible existence of hidden faults or unnecessary operation of the protections for testing purposes. The obtained EIS security indicators show the impact of the operating sequence of protection devices on them. In this way, the proposed methodology offers a solid conceptual fundament and a practical tool for the analysis and design of EIS and power systems.

Section II presents the PNs theory fundamentals; while Section III develops the methodology of sequence operation modeling to be used in security evaluation. Then, Section IV shows the application of the proposed methodology using the IEEE 493. Section V presents the result analysis and Section VI the main conclusions.

II. Petri Nets (PN)

A petri network is a graphical and mathematical tool to model synchronization process, asynchronous events, sequential operations, concurrent operations, conflicts and resources management [14]. 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, PNs are very useful for the analysis of various industrial processes such as production facilities, modeling of electrical systems, and computational systems.

A PN is a particular kind of bipartite directed graph that comprises several sets, which are nodes and arcs. The first group is divided into transitions (T) and places (P), which represents the states and events that allow moving from one state to another. Each element has its respective set; for instance, for the transitions: $T = \{t_1, t_2, \ldots, t_n\}$ and for places: $P = \{p_1, p_2, \ldots, p_n\}$. The second group connect places with transitions and *vice versa* [15].

There are also Tokens, that show graphically the availability of places. The Tokens are those dots inside the places into the scheme. Fig. 1 shows all the elements of PNs. One particular state of a PN is defined by the number of tokens contained in each place denoted by a marking vector M [14]. After that, a coverability graph is built from the possible sequence of transitions [16].

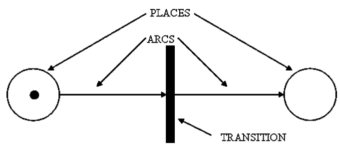

Fig. 1. PNs representation.

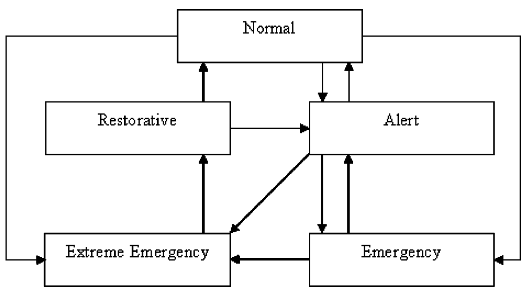

Fig. 2. Operating states in EIS [19].

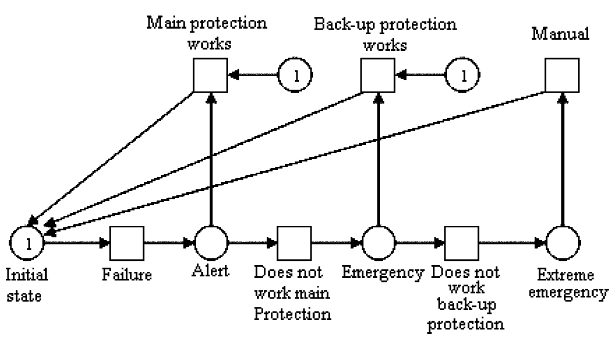

Fig. 3. Proposed methodology for PN models of protection systems [24].

A coverability graph is a useful concept of PNs, specifically of marked PN [15]. This model allows to evaluate the property of reachability in a PN, 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. Furthermore, coverability graph allows the study of other properties of PNs, e.g., liveness and reversibility [15].

There are many types of PNs. The most important are: marked PNs, temporized PNs and stochastic PNs (SPN) [15]–[18]. Stochastic petri networks are used when the transition time takes stochastic values. Therefore, this random variable follows an exponential law and, consequently, the SPN represents a homogeneous Markovian process. A GSPN is used if the model includes not only exponential time transitions, but also instantanous or inmediate transitions [18].

Marked PNs are mostly used to evaluate quantitatively the systems. This method gives important information as security and suitable system performance. Similarly, it can use probability values in order to solve conflicts between transitions; e.g., when there are two or more possible values to be fired. PN are solved by simulation and it has been used to evaluate the reliability of power systems [11].

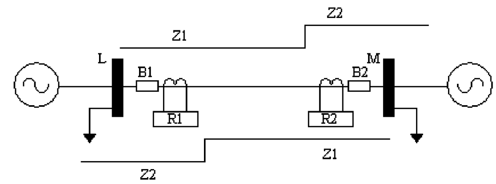

Fig. 4. 2-buses system.

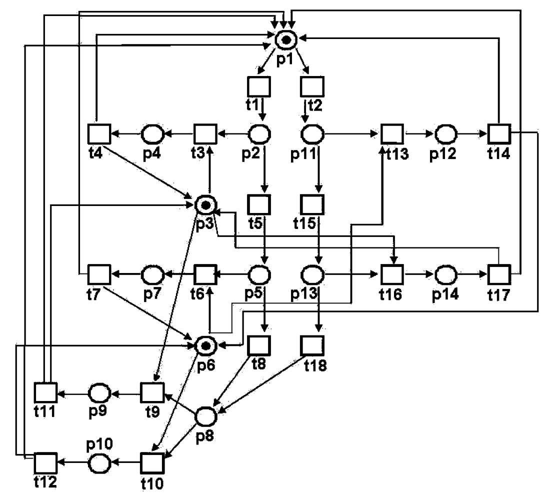

Fig. 5. PN for 2 buses system.

III. Security Assessment With PNs

Security is defined as the ability of the power system to respond to sudden disturbances without supply interruption. Therefore, security analysis must evaluate nonappropriate 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.

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 [19]. Fig. 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 nonsecure state if it is in emergency or extreme emergency state.

The main components to define the operating states of the EIS according to Fig. 2, which are taken into account for the formulation of the PN, 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.

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

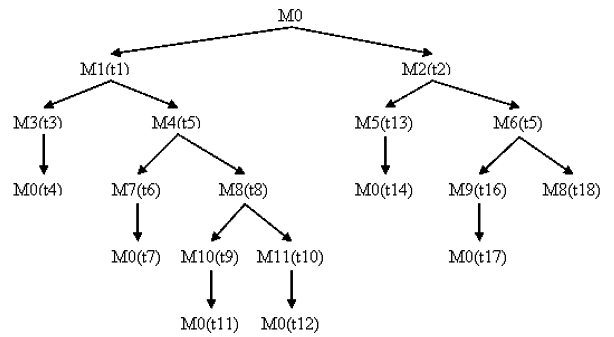

Fig. 6. Coverability tree of PN for 2 buses system.

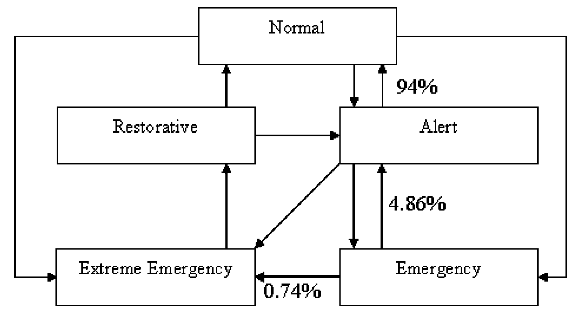

Fig. 7. Simulation results for 2-buses system.

TABLE I
PNs PLACES FOR 2 BUSES SYSTEM

Place	Description
p1	Initial state
p2	Fault close to bus L state
p3	Availability of main protection
p4, p12	Isolation of fault by main protection
p5, p13	Emergency state
p6	Availability of back-up protection
p7, p14	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

TABLE II
PNs TRANSITIONS FOR 2 BUSES SYSTEM

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

when they are needed, is equivalent to the conditional probability of nonoperation when the disturbance is present [20].

In power systems and the EIS, the nonsecure 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.

Once a PN is built for a system, it is necessary to identify those places (P) that correspond to each operating states in Fig. 2. 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 follows.

1) Definition of the event to be analyzed.
2) System definition: Identification of protective devices, 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 PN structure. For instance, for each fault in a power system the PN model is built according to Fig. 3.
5) Assign an operating state for each place in the PN.
6) Simulation and validation of the PN model.
7) Generation of the coverability graph and identification of the operating state of the system.
8) Security index assessment.

IV. APPLICATIONS OF THE METHODOLOGY

The main characteristic of protections in a meshed power system is that load and fault currents flow either counterclockwise or clockwise [13]. Thus, in order to model the PNs, the coordination of protections in a meshed Power Ssystem is fundamental. Indeed, definition of protection zones for distance relays is the most important theory in order to specify the operating sequences of protections (main and back-up) in power transmission systems using PNs [13], [21]–[23].

Jenkins modeled the main and back-up protections using Stochastic PNs [20], applied to single radial systems without considering uncertainty in the appropriate response of the protection device; such uncertainty is analyzed below. Also, Wang and Tang [25] proposed a model for a transmission line with three different relays on the same line. As well, they suggested to study the relationship between protections in bulk power systems using a high-level software. However, their proposal does not evaluate the impact on the power system when a failure of the protection systems occurs.

A. 2-Buses System

Fig. 4 presents a radial power system with 2 buses, which will be analyzed in order to apply the proposed methodology for modeling protection sequences with PNs. Considering two possible faults with the same probability of occurrence, the first one is located close to bus L, and the second one close to bus M. The PN for this system is presented in Fig. 5. As well, place and transition descriptions are in Tables I and II.

Conditions of power systems are described by five operating states [26], three of which are alert state, emergency state, and extreme emergency (main protection fired, back-up protection fired, and manual operation, respectively). For the above system (2 buses), the PN is simulated with PetriNet Toolbox [27], and the results—using a failure probability of 5% of each protection device when it is required to operate—are shown in Fig. 7.

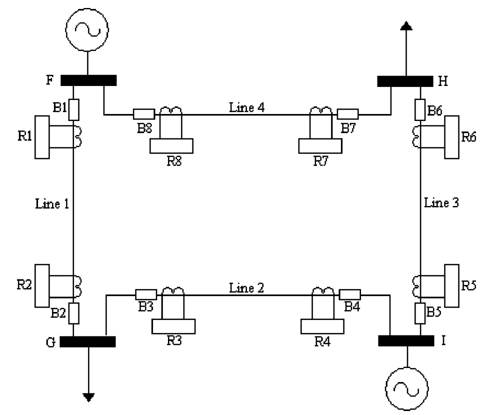

Fig. 8. 4-buses system.

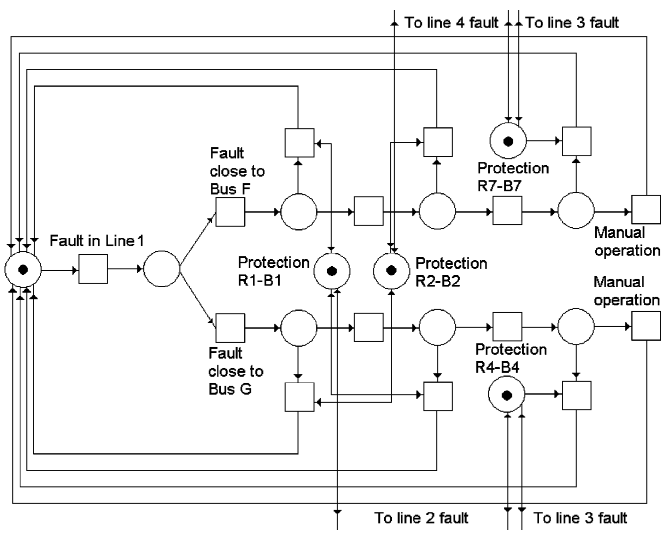

Fig. 9. Sub-PN for 4 buses system.

TABLE III
RESULTS BY STATE

System	Alert	Emergency	Extreme Emergency
2 buses	94.9%	4.86%	0.74%
4 buses	95.2%	4.56%	0.24%

B. 4-Buses System

The next model presents a meshed 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. 8 and the Sub-PN modeled is presented in Fig. 9, 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 PN, 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.

Finally, Table III shows a summary of simulations presented in this section.

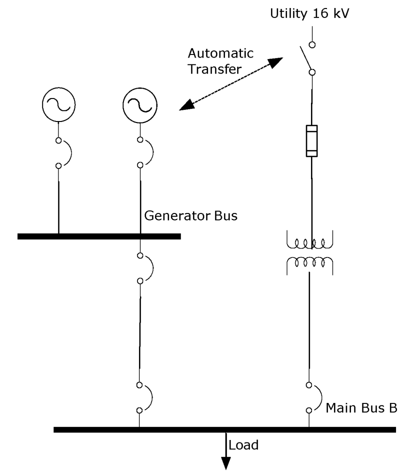

Fig. 10. Automatic transfer system scheme IEEE 493 test system.

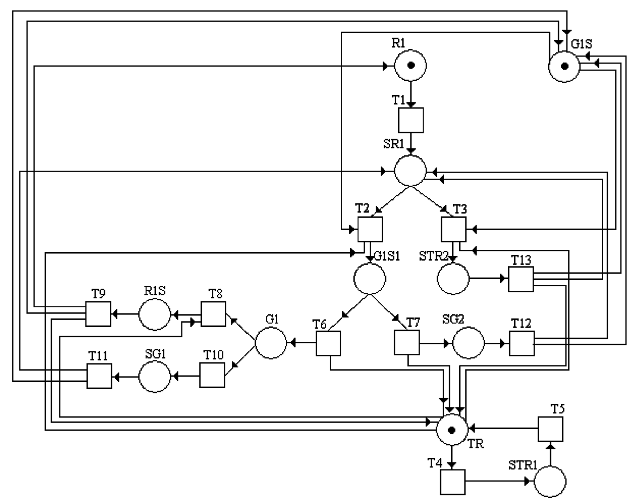

Fig. 11. Petri network for transfer system.

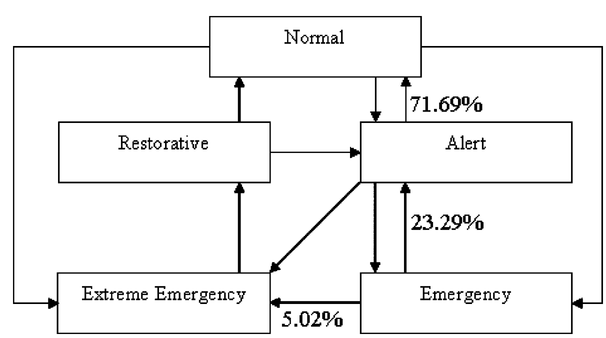

Fig. 12. Probabilities of operating states for transfer system.

C. IEEE 493 System

Test System: The electric supply of the IEEE 493 system [5] 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 system, 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

TABLE IV
PLACES FOR THE PN REPRESENTATION OF THE TRANSFER SYSTEM

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 V
TRANSITIONS 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

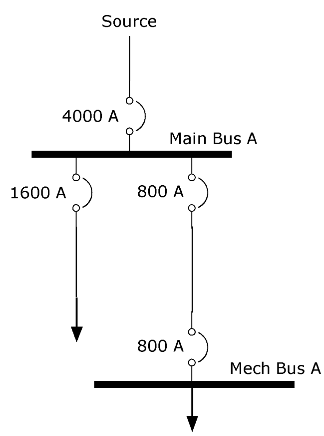

Fig. 13. Load system scheme IEEE 493 test system.

generators are required to meet the network load demand at all time [6].

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.

1) 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 [28].

Table IV lists the places or system states that can be reached by the system when an outage occurs and Table V presents the transitions of the states. So, from Tables IV and V 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.

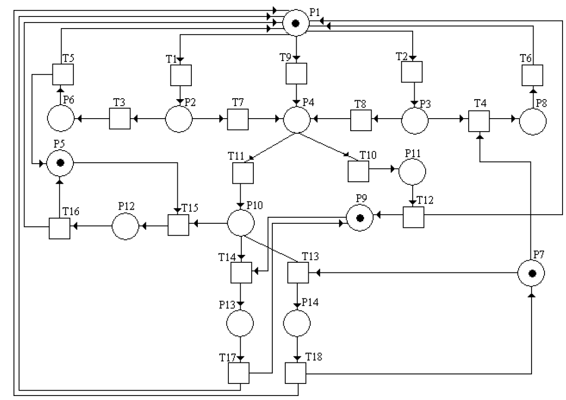

Fig. 14. Petri network for load system.

TABLE VI
PLACES FOR THE PN REPRESENTATION OF THE LOAD SYSTEM

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 VII
TRANSITIONS FOR THE PN REPRESENTATION OF THE 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

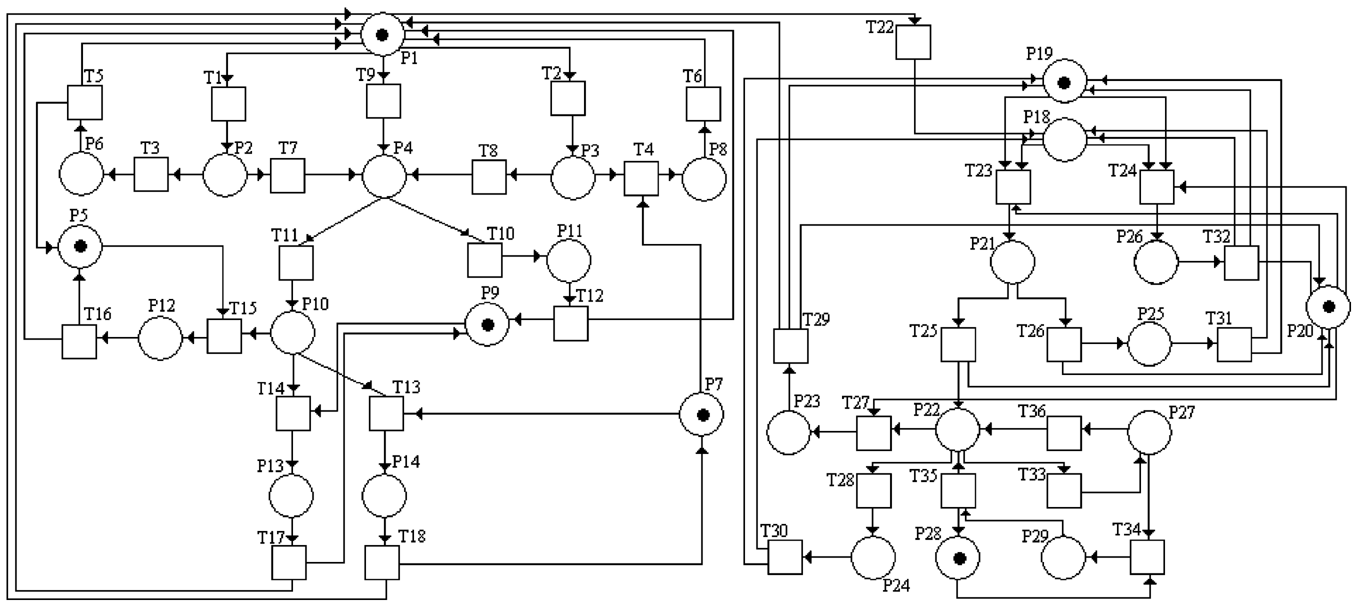

Fig. 15. Petri network for total system.

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. 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.

2) 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%.

Table VI lists the places or system states that can be reached by the system when an outage occurs and Table VI presents the states' transitions. Tables VI and VII show 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.

V. Analysis of the Total System

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

The connection between these PNs 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.

VI. Conclusions and Further Work

This paper has proposed a methodology of security assessment of EIS and power systems based on PNs 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 PN models' places, in order to determine the PN Places that model the nonsecure operating states.

This paper has shown that petri networks are useful tools for computing security indexes for power systems. So, the proposed technique allows the security analysis of industrial electrical systems and power systems, taking into account hidden failures and the sequence of operation in protection devices.

The 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 EIS 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 PNs for assessment of larger power systems requires the use of High-level PNs, e.g., Colored PNs.

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