MODELLING RELIABILITY OF DISTRIBUTION NETWORK FAULT DIAGNOSTIC TOOLS USING PETRI-NETS

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ABSTRACT
The aim of the work presented in this paper is to evaluate and develop a framework for reliability analysis of distribution system modeling and simulation using Petri-Nets. The problem of detecting, isolating and restoring fault events in dynamic systems modeled is considered. As the complexity of power system increases, fault diagnosis become very difficult task therefore necessitate the development of PN to anchor onto power system in order to tackle and overcome these situation. A sample power system network which has 2 sources, 4 buses, 10 over current relays, 5 circuit breakers and 2 distribution lines connected loads is used as test network. The modeled network is then simulated with five fault cases. Results of these simulations are given in order of the PN firing sequence as follows: $M_1 = (1; 0; 0; 0; 0; 0; 0)$; $M_2 = (0; 1; 0; 0; 0; 0; 0)$; $M_3 = (0; 0; 1; 1; 0; 0; 0)$; $M_4 = (0; 0; 1; 0; 1; 1; 0)$; $M_5 = (0; 0; 1; 0; 1; 0; 1)$ *and* $M_6 = (1; 0; 0; 0; 0; 0; 0)$.*It is shown from five cases that the faulted power system elements are diagnosed accurately by using the Petri nets based fault diagnosis models analytical and simulation.*
Keywords: distribution network, fault analysis, petri-nets, firing token and reliability.

1. INTRODUCTION
The basic function of modern electric power system is to provide an adequate electrical supply to its customers as economically as possible and at an acceptable level of reliability. Electric distribution system is one of the key components of electric power supply system. Its reliability has an important impact on the system safety performances.

Most of the work in literature use information from circuit breakers and relays which are gathered via Supervisory Control and Data Acquisition (SCADA) systems in order to determine the nature of fault. Time information, sequence of events, is also used in some proposed solutions where data is available (Minakawa *et al*, 1995), while others used rule based systems sharing some basic properties.

A Petri Net (also known as place/transition net or P/T Net) is one of the several mathematical modeling tools such as ANN, Fuzzy Logic, Fault Tree etc. that are used for the description of distribution reliability systems. A Petri Net is a directed bipartite graph, in which the nodes are represented by transitions and places. The places are represented by a circle while the transitions are represented by a bar or rectangle, and the arcs connect these nodes. The connections from place to transition signify the input while from transition to place signifies the output.

Fault diagnosis in power systems has been conventionally performed by human operators at the control centers based on information collected from distributed sensors. Fault diagnosis requires information from the SCADA system. Basically, when the information comes to the control center, the operators analyze the data and diagnose the fault. However, as the complexity of the power systems increases, especially in the case of multiple faults or incorrect operation of the protective devices, the amount of information needed to be processed and evaluated exceeds the human capability. For this reason, computer based systems have been developed to aid operators carry out such complex reasoning process. In this study a simple model with Petri Nets based solution to the fault diagnosis in electrical distribution systems has been developed. A power system network which has buses, over current relays, circuit breakers, distribution lines and loads is used as test network, with all their parameters structure information embedded.

1.2. State of the Art
Petri- Net was first developed by Carl Adam Petri in 1962. After him, several researchers have employed his idea and developed different models in other related fields. This application is a powerful modeling formalism in electrical engineering, computer science, system engineering and many other disciplines. Petri Nets combine a well defined mathematical theory with a graphical representation of the dynamic behavior of systems. The theoretic aspects of the application allow precise modeling and analysis of system behavior, while the graphical representation enables visualization of the modeled system state changes. Petri Nets have been used to model various kinds of dynamic event-driven systems like computer networks and control (Ajmone) (Andreadakis and Levis, 1988) (Murata, 1989) (Mandriolis *et a., 1996)*, manufacturing plants (Verkatesh et al. 1994), logistic networks and workflows (Landreghem *et al*., 2000) (Aalst and Van, 2004) (Chuang et al., 2003), communication systems (Wang, 2007), to mention only a few important examples. This wide spectrum of applications is accompanied by wide spectrum different aspects which have been considered in the research work. In power system and fault diagnosis; (Lo et al., 1997) Liu and Chiou, 1997)

(Hadjicostis and Verghese, 2000) (Vitali, 2004) (Frankowiak et al., 2005) (Pamuk and Uyaroglu, 2012) have proposed a power system fault diagnosis using Petri Nets.

1.3. Modeling Capabilities of Petri-Nets

Several typical characteristics of modeling exhibited by the activities in a dynamic state, such as concurrency, decision making, synchronization and priorities, can be modeled effectively by Petri Nets as shown in Figure 1 (Wang, 2007).

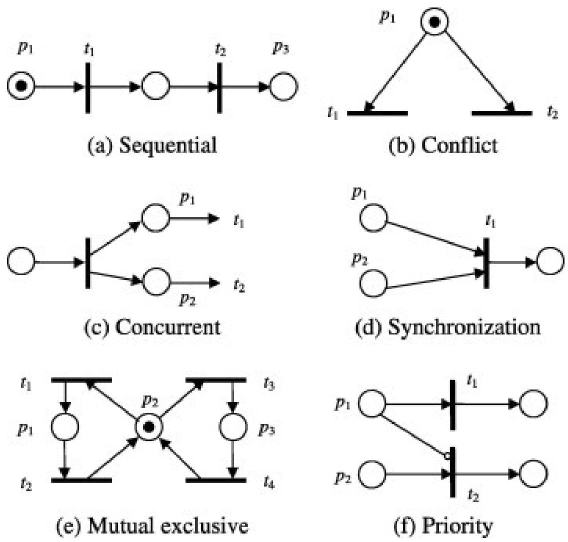

Figure 1: Petri Net Primitives Represent System Features (Wang, 2007)

Figure 1 described the primitive representation of PN modeling. Each model is briefly described as follow:

Sequential Execution; in Figure 1.1(a), transition t_2 can be fire only after the firing of t_1. This imposes the precedence constraint "t_2 after t_1."

Conflict; transitions t_1 and t_2 are in conflict in Figure 1.1(b). Both are enabled but the firing of any transition leads to the disabling of the other transition. The resulting conflict may be resolved in a purely non-deterministic way or in a probabilistic way, by assigning appropriate probabilities to the conflicting transitions.

Concurrency; in Figure 1.1(c) the transitions t_1, and t_2 are concurrent. Concurrency is an important attribute of system interactions. Note that a necessary condition for transitions to be concurrent is the existence of a forking transition that deposits a token in two or more output places.

Synchronization; the resulting synchronization of resources can be captured by transitions of the type shown in Figure 1.1(d). Here, t_1 is enabled only when each of p_1 and p_2 receives a token.

Mutually exclusive; Figure 1.1(e) shows this structure. Two processes are mutually exclusive if they cannot be performed at the same time due to constraints on the usage of shared resources.

Priorities; a Petri Net with an inhibitor arc is shown in Figure 1.1(f) t_1 is enabled if p_1 contains a token, while t_2 is enabled if p_2 contains a token and p_1 has no token. This gives priority to t_1 over t_2. The inhibitor arc connects an input place to a transition, and is pictorially represented by an arc terminated with a small circle.

1.4. Basic Notation and Structure of a Petri Net

Mathematically, a Petri Net (PN is defined as a quintuple (5) (Peterson, 1997), (*P; T; I;O;M*), where:

$P = \{p_1; p_2 \ldots\ldots\ldots\ p_n\}$ is the set of n_p places (drawn as circles in the graphical representation);

$T = \{t_1; t_2 \ldots\ldots\ldots\ldots\ldots.. tn\}$ is the set of *nt* transitions (drawn as bars);

I is the transition input arcs directed from places to transitions;

O is the transition output arcs directed from transitions to places;

$M = \{m_1; m_2; \ldots\ldots\ldots; mn\}$ is the marking. The generic entry *mi* is the number of tokens (drawn as black dots) in place *pi* in marking *M*.

The graphical structure of a PN as earlier stated is a bipartite directed graph: the nodes belong to two different classes (places and transitions) and the edges (arcs) are allowed to connect only nodes of different classes (multiple arcs are possible in the definition of the I and O relations.

The dynamics of a PN is obtained by moving the tokens in the places by means of the following execution rules: a). A transition is enabled in a marking *M* if all its input places carry at least one token; b). an enabled transition fires by removing one token per arc from each input place and adding one token per arc to each output place.

To get an initial marking M_1, a black dot in the Centre of the circle P_1 in Figure 2 is assigned. The reachability set $R(M_1)$ which is one of the properties of PN is the set of all the markings that can be obtained by repeated application of the above rules.

1.5. Modeling of Petri Nets

A Petri Net is a collection of directed arcs connecting places and transitions. Places may hold tokens. Petri Nets are used in computer systems, manufacturing systems and power protection systems modeling (Murata, 1989). A Petri Net PN is defined by the set of places P, the set of transitions T, the input function D^-, and the output function D^+. A Petri Net model is illustrated in Figure 2.

First, three special matrices should be formed which are used to explain relations in the net: Input, Output and Incidence matrices. All three matrices have P columns and T rows. First the input matrix will be obtained as follows. If there is an arc from a place to a transition then corresponding element of the input matrix has a value which is equal to capacity of the arc, else value of that element is 0. Hence the input matrix is formed as (Peterson, 1997).

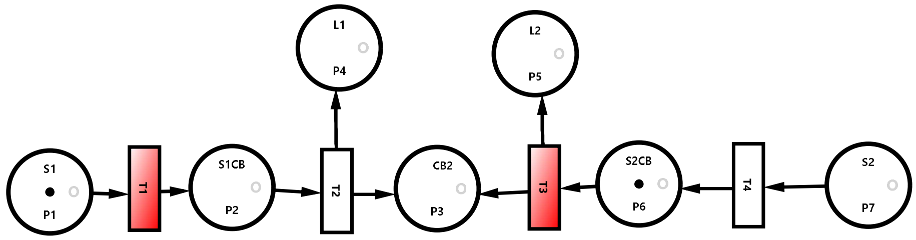

Figure 2 Petri Net Model of network system

$$D^- = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

If there is an arc from a transition to a place then corresponding element of the output matrix has a value which is equal to capacity of the arc, else the value of that element is 0. Hence the output matrix is formed as [17]:

$$D^+ = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (2)$$

The topological structure of a Petri Net is represented with incidence (D) matrix. The D matrix is defined as [17]:

$$X(p,t) = \begin{cases} D^-(p,t), if\ f(p,t) \in F \\ D^+(t,p), if\ f(t,p) \in F \\ 0, \ otherwise \end{cases} \quad (3)$$

Where $D^{-/+}(p, t)$ is the weight of the arc from place (p) to transition (t) and F is the flow relation between place and transition. Hence:

$$D = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \quad (4)$$

Token distribution is shown with marking vector. So for the Petri Net in Figure 2, the initial marking vector $M_0(s)$ is $[1\ 0\ 0\ 0\ 0\ 1\ 0]^T$. Markings and executions define the dynamic properties of the net. Execution is defined as the firing of the transition of a net which changes the marking of the net by moving tokens from their input places to their output places. A transition is enabled if all its input places have at least the same number of tokens. For example, the dynamic behavior for the PN steady state in Figure 2 is given as, (Peterson, 1997): Firing t_1 results in M_1

$$M1 = M0 + CU \quad (5)$$

$$M_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} + \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad (6)$$

$$M_1 = \begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (7)$$

2. METHODOLOGY

The proposed diagnostic procedure to consider the final information of the circuit breakers and protective relays is received by SCADA system. Putting that information into the Petri net fault diagnosis model, and then determine the faulty section as follows:

Represent the initial token distribution of the Petri net by M_o. Determine the vector U_1 by the transition status as a fault state in Petri net. Build the incidence matrix C according to Petri net model and Eqn. (3). Determine the dynamic transition process of the Petri net M_1 according to Eqn. (5). Through vector M_1, redistribute the token after the first firing. Determine the vector U_2 by the transition status. Determine the second dynamic transition process of the Petri net M_2 according to Eqn. (5) and finally, specify the faulted section with the place that includes one token at least.

The analysis of diagnosis process is presented and demonstrated in the following figures. In Figure 3, it is supposed that a fault occurred in node L_1, and the information received from SCADA is; L_2 relay and L_2CB are operated. Where L_2P_7 includes L_2 relay then L_2P_7 in the model operates, so the initial token distribution can be determined as shown in Figure 3. In this case, the transition T_4 matches the firing condition and then fires. The initial token distribution marking is represented by M_o as shown as follows:

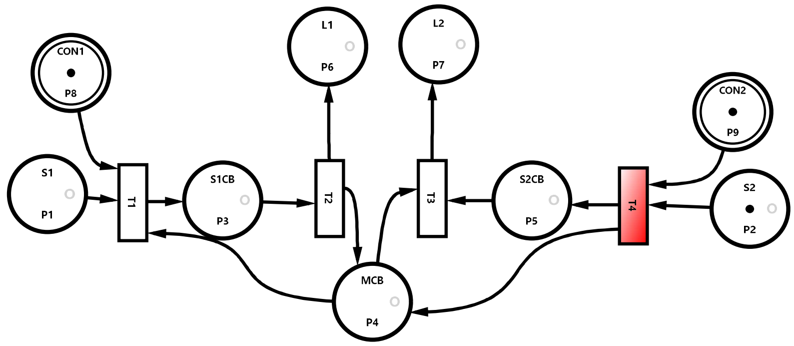

Figure 3. The initial Token Distribution of the Net

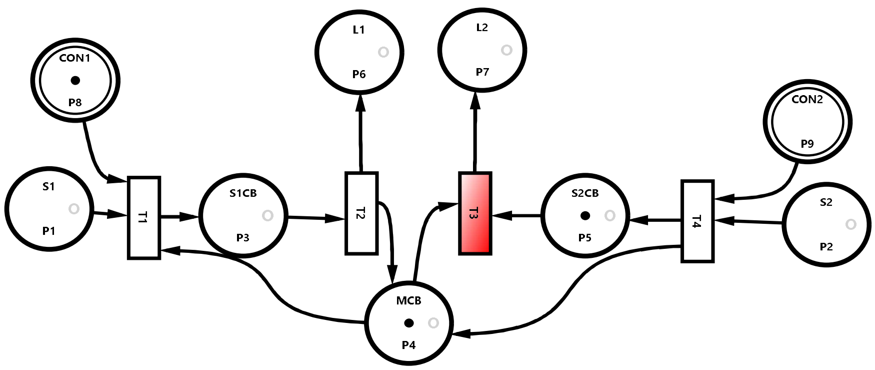

Figure 4 Token Redistribution Status of the Net

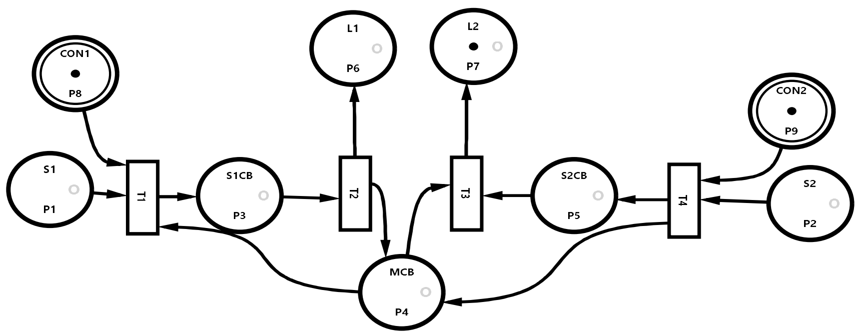

Figure 5 Final Token Distribution of the Petri net in S2.

$$M_0 = \begin{bmatrix} S1 & S2 & S1CB & MCB & S2CB & L1 & L2 & CON1 & CON2 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}^T \quad (8)$$

According to the Petri net model equation, the incidence matrix C can be obtained as follows:

$$C = \begin{bmatrix} S1 & S2 & S1CB & MCB & S2CB & L1 & L2 & CON1 & CON2 & \\ -1 & 0 & 1 & -1 & 0 & 0 & 0 & -1 & 0 & t1 \\ 0 & 0 & -1 & 1 & 0 & 1 & 0 & 0 & 0 & t2 \\ 0 & 0 & 0 & -1 & -1 & 0 & 1 & 0 & 0 & t3 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & t4 \end{bmatrix} \quad (9)$$

According to eqn. (5), M_1 is given as:

$M_1 = (M0 + CU)$, where U is $[M_0]^T$

$$M_1 = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \quad (10)$$

Through vector M_1 , the token distribution after the first firing as shown in Figure 4. Finally, determine vector M_2 as follows:

$$M_2 = M1 + CU; \text{ then,}$$

$$M_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & 1 \end{bmatrix} \quad (11)$$

In this case, as shown in Figure 5, there is no longer transition being fired. Therefore, the present Petri net has reached to its stable status. That means, the place which includes one token at least become the faulted section. The example shows the place L_2 (distribution line 2) has one token, and then, the faulted section is distribution line 2.

3. RESULTS AND DISCUSION OF DYNAMIC STATES IN PN MODELING OF THE FIRING SEQUENCES.

The vector $\mu = (\mu_1, \mu_2, \mu_3, \ldots\ldots\ldots, \mu_n)$ gives, for each place in the Petri net, the number of tokens in that place p_i is μ_i $i=1\ldots\ldots\ldots n$. On a Petri net graph, tokens are represented by small solid dots inside the circles representing the place of the net. Figures 6 and 7 are an example of a Petri net graph with marking.

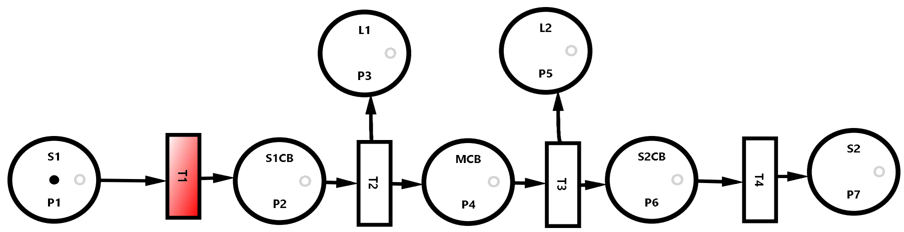

Figure 6 The initial state of PN model

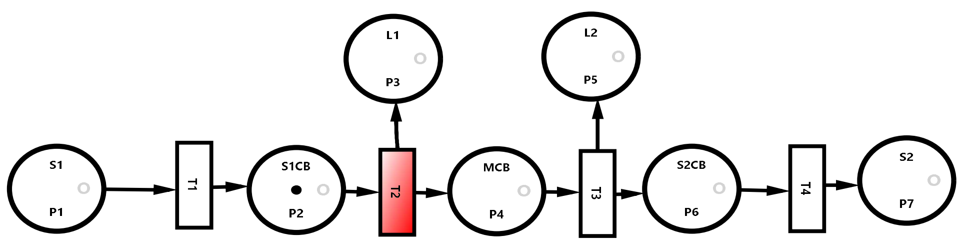

Figure 7 The first fired state of PN model

Following the above-mentioned rules, the place S_1 (ie p_1) is assigned a token. The initial state of PN model of the distribution lines L_1 and L_2 is given in Figure 7. As a result, the initial marking vector M_1 is given by: $M_1 = (1; 0; 0; 0; 0; 0; 0)$. In M_1 the only enabled transition is t_1; firing t_1 removes the token from p_1 and put a token in p_2 producing new marking in Figure 7, $M_2 = (0; 1; 0; 0; 0; 0; 0)$. With this, all the possible firing sequences have been examined, and the reach ability set $R(M_1)$ of the net of Figure 6 turns out to contain six elements M_1, M_2, M_3, M_4, M_5 and M_6

The summary of the vector $\mu = (\mu 1, \mu 2, \ldots\ldots \mu n)$ firing results are obtained in the following sequence, Figure 8:

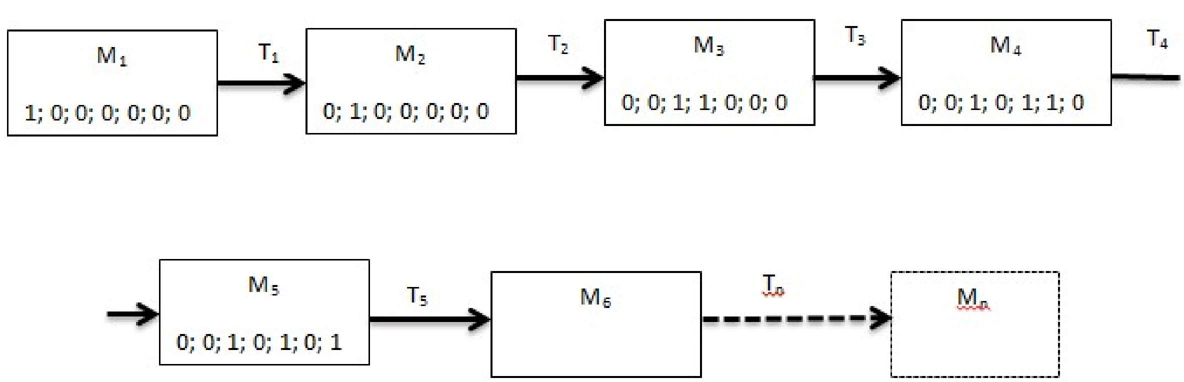

Figure 8: Vector μ Firing Sequence Results.

4. CONCLUSION

A proposed approach base on PNS was suggested for modeling of the power system. In this method, the model of protection systems performed has been formulated using PNS. The proposed method uses information from relays and circuit breakers to evaluate the system condition and to make diagnosis. If the entire protection device fails to interrupt the fault, then a backup Protection will operate. This model is good for the fault diagnosis of power system and it reduces the outage frequency and quick restoration of the outages.

Reference

Aalst Van Der, W., & Van Hee, K. M. (2004). *Workflow management: models, methods, and systems*. MIT press.

Ajmone Marsan, M., Balbo, G., & Conte, G. (2000). The Early Days of GSPNs. In *Performance Evaluatio: Origins and Directions* (pp. 505-512). Springer Berlin Heidelberg.

Andreadakis, S. K., & Levis, A. H. (1988). *Synthesis of distributed command and control for the outer air battle* (No. LIDS-P-1790). Massachusetts Inst of Tech Cambridge lab for information and decision systems.

Chuang, L. I. N., QUYang, R., & Marinescu, D. C. (2003, August). Performance equivalent analysis of workflow systems. In *Engineering and Deployment of Cooperative Information Systems: First International Conference, EDCIS 2002, Beijing, China, September 17-20, 2002. Proceedings* (Vol. 2480, p. 64). Springer.

Frankowiak, M. R., Grosvenor, R. I., & Prickett, P. W. (2005). A Petri-net based distributed monitoring system using PIC microcontrollers. *Microprocessors and Microsystems*, *29*(5), 189-196.

Hadjicostis, C. N., & Verghese, G. C. (2000, September). Power system monitoring using Petri net embeddings. In *Generation, Transmission and Distribution, IEE Proceedings-* (Vol. 147, No. 5, pp. 299-303). IET.

Liu, T. S., & Chiou, S. B. (1997). The application of Petri nets to failure analysis. *Reliability Engineering & System Safety*, *57*(2), 129-142.

Lo, K. L., Ng, H. S., & Trecat, J. (1997, May). Power systems fault diagnosis using Petri nets. In *Generation, Transmission and Distribution, IEE Proceedings-* (Vol. 144, No. 3, pp. 231-236). IET.

Mandrioli, D., Morzenti, A., Pezze, M., Pietro, P., & Silva, S. (1996). A Petri net and logic approach to the specification and verification of real time systems. *Formal Methods for Real-Time Computing*, *5*.

Minakawa, T., Ichikawa, Y., Kunugi, M., Shimada, K., Wada, N., & Utsunomiya, M. (1995). Development and implementation of a power system fault diagnosis expert system. *Power Systems, IEEE Transactions on*, *10*(2), 932-940.

Murata, T. (1989). Petri nets: Properties, analysis and applications. *Proceedings of the IEEE*, *77*(4), 541-580.

Pamuk, N., & Uyaroglu, Y. (2012). The fault diagnosis for power system using fuzzy Petri nets. *Przeglad Elektrotechniczny*, *88*(7A), 99-102.

Peterson, James L. "Petri net theory and the modeling of systems." (1981).

Landeghem Van R., & Bobeanu, C. V. (2002). Formal modelling of supply chain: An incremental approach using Petri nets. In *14th European Simulation Symposium and Exhibition: Simulation in Industry–Modeling, Simulation and Optimization (ESS 2002, Proceedings)* (pp. 323-327).

Venkatesh, K., Zhou, M., & Caudill, R. (1994, November). Evaluating the complexity of Petri nets and ladder logic diagrams for sequence controllers design in flexible automation. In *Emerging Technologies and Factory Automation, 1994. ETFA'94., IEEE Symposium on* (pp. 428-435). IEEE.

Vitali Volovoi, (2004). Modeling of system reliability Petri nets with aging tokens. *Reliability Engineering & System Safety*, *84*(2), 149-161.

Wang, J. (2007). Petri nets for dynamic event-driven system modeling. *Handbook of Dynamic System Modeling*, 1-17.