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An Expert System for Power Transformer Fault Diagnosis Using Advanced Generalized Stochastic Petri Net

***Abstract**. Power transformers are considered as one of the essential elements in electrical networks. Power transformer fault diagnosis and repair is a complex task that includes many possible types of faults and demands special trained personnel. Any failure in these equipments directly reduces network reliability and increases maintenance costs.The paper mainly investigates fault diagnosis of power transformer by using Advanced Generalized Stochastic Petri Net (AGSPN) technology. AGSPN is used for accurately fault diagnosis in power transformer when some incomplete and uncertain alarm information of protective relays. After reviewing the AGSPN theory, the models of fault diagnosis for power transformer are built. Simulation results for the most common types of transformer faults (short circuit, insulation failure, oil leakage and overloading) are presented. The obtained results are ultimately interesting and applicable for maintenance and fault diagnosis engineers to quickly fault diagnosis on the scene. Finally, the proposed method can easily be adapted to different power system elements.*

***Streszczenie.** W artykule badano metody diagnozowania uszkodzeń transformatorów przy użyciu metody AGSPN (Advanced Generalized Stochastic Petrio Net). Sklasyfikowano możliwe uszkodzenia sprawdzono metodę symulacyjne. (**System ekspertowy diagnozowania uszkodzeń transformatorów przy wykorzystaniu sieci Petriego**)*

Keywords: Power transformer, fault diagnosis, expert system, advanced generalized stochastic petri nets.
Słowa kluczowe: transformatory mocy, diagnozowanie, sieci Petriego

Introduction

Electricity markets have become increasingly competitive over the last few years. To limit costs, electricity companies are often forced to decline their investments by using aging equipment and by overloading their power transformers [1, 2]. Nevertheless, these transformers are one of the most dangerous electrical equipments because of the large quantity of oil they contain in direct contact with high voltage elements [3]. Despite all these risks, and contrarily to pressure vessels, no specific standards have been set to design.

Power system reliability depends on the reliability of the components in the system [4, 5]. Therefore oil filled transformer explosions are more and more frequent. They result in dangerous fires most of the time, with very expensive damages and possible environmental pollution. Since the ultimate element in the electricity supply chain, the power transformer is one of the most widespread apparatus in electric power systems [6]. For all these reasons, power transformer explosions and their prevention are becoming a critical industrial issue. When a power transformer fault occurs, it is essential to identify the fault type and to minimize the time needed for transformer repair, especially in cases where the continuity of supply is vital. Thus, it should not come as a surprise that power transformer fault diagnosis forms a subject of a permanent research effort.

Diverse power transformer fault diagnosis techniques have been suggested in the literature, for different types of faults [7]. For thermal related faults, the most significant diagnostic method is the gases in oil analysis [8, 9] while other methods such as the compounds analysis, the degree of polymerization and the thermograph are also applicable [10]. For dielectric related faults, it is necessary to localize and to characterize the partial discharge source, so as to give a correct diagnosis after receiving an alarm signal via gas in oil sampling or via sensors [11]. For mechanical related faults, the frequency response analysis and the leakage inductance methods are the more frequently used transformer fault diagnosis techniques [12]. Eventually, for power transformer general degradation, the dielectric response, the oil analysis and the compounds analysis methods are applicable [13].

Despite the extensive range of the power transformer fault diagnosis methods, the diagnostic criteria developed till today are not totally applicable to all faulty cases, and as a consequence, the experience of experts still play an essential function in the diagnosis of the power transformer faults. Artificial intelligence techniques and expert systems have already been suggested to understand the obvious and non-obvious relationships between power transformer failures and the causes of failures. Preliminary results, attained from the application of these techniques, are encouraging, however some limitations exist. Knowledge acquisition, knowledge representation and maintenance of a great number of rules in the expert systems require plenty of efforts [7].

In this paper, AGSPN are suggested for modelling of power transformer fault diagnosis process. AGSPN are both a graphical and mathematical tool capable of capturing stochastic or deterministic system behaviour and modelling phenomena such as parallelism, sequential, asynchronous behaviour, resource sharing, conflicts and mutual exclusion [12]. The suggested method offers crucial advantages such as visual representation of the above actions, systematic determination of the sequence of fault diagnosis and repair actions, as well as prediction of the time needed for power transformer repair.

Petri net principles

A Petri nets (PN) may be identified as a particular kind of bipartite directed graphs populated by three types of objects. These objects are places, transitions and directed arcs connecting places to transitions and transitions to place. Pictorially, places are depicted by circles, and transitions are depicted by bars or boxes. In its simplest form, a PN may be represented by a transition together with its input and output places. PN may be used to represent various aspects of the modeled systems. In order to study dynamic behavior of the modeled system, in terms of its states and their changes, each place may potentially hold either none or a positive number of tokens, pictured by small solid dots. The presence or absence of a token in a place can indicate whether a condition associated with this place is true or false, for instance.

A PN is a 5-tuple [14] $N = (P, T, I, O, M_0)$, where

(1) $P = \{p_1, p_2, \ldots, p_m\}$ is a finite set of places;

(2) $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions; $P \cup T \neq \emptyset$, and $P \cap T = \emptyset$;

(3) $I : (PXT) \rightarrow N$ is an input function that defines directed arcs from places to transitions, where N is a set of nonnegative integers;

(4) O : (PXT) $\rightarrow$ N is an output function that defines directed arcs from transitions to places; and
(5) M_0 : P $\rightarrow$ N is the initial marking.

A marking is an assignment of tokens to the places of a PN. A token is a primitive concept for PN (like places and transitions). Tokens are assigned to, and can be thought to reside in, the places of a PN. The number and position of tokens may change during the execution of a PN. The tokens are used to define the execution of a PN.

Advanced generalized stochastic petri nets (AGSPN)

AGSPN is a 6-tuple [15] (P, T, I, O, M_0, Λ) in which (P, T, I, O, M_0) is a PN and Λ : T $\rightarrow$ R is a set of firing rates whose entry λ_k is the rate of the exponential individual firing time distribution G_k (x \ M) associated with transition t_k.

Definition 1: Let (P, T, I, O, M_0, Λ) be an AGSPN. Given M_i, $M_j \in$ R (M_0), there exists a specific probability a_{ij} of reaching M_j immediately after exiting from M_i.

Define T_{ij} = { t $\in$ E (M_i) : M_i [t > M_j } There are two possibilities: T_{ij} = Ø and $T_{ij} \neq$ Ø. If T_{ij} is empty, we have that M_j cannot be reached from M_i in single step and hence a_{ij} = 0. Now consider the case when T_{ij} is non-empty. Let

(1) $$rij = \sum_{tk \in Tij} \lambda k$$

(2) $$ri = \sum_{tk \in E(Mi)} \lambda k$$

The probablity of marking M_i changing to M_j is the same as the probablity that one of the transitions in the set T_{ij} fires before any of the transitions in the set T \ T_{ij}. Since the firing times in an AGSPN are mutually independent exponential random variables, it follows that the required probability has the specific value given by $a_{ij} = r_{ij} / r_i$. In the expression for a_{ij} deduced above, note that the numerator is the sum of the rates of those enabled transitions in M_i, the firing of any of which changes the marking from M_i to M_j ; whereas the denominator is the sum of the rates of all the enabled transitions in M_i. Also note that a_{ij} = 1 if and only if T_{ij}=E(M_i).

Definition 2: The sojourn time of any reachable marking in an AGSPN is exponentially distributed.

Let $M_i \in$ R (M_0), suppose that E' (M_i) is the subset of E (M_i) comprising all transitions such that the firing of any of which in M_i would lead to marking other than M_i. Let

(3) $$ri' = \sum_{tk \in E'(Mi)} \lambda k$$

The sojourn time in Mi is a random variable given by

(4) $$\min_{tk \in E'(Mi)} \exp(\lambda k)$$

Then by the mutual independence of the firing times, it follows that the sojourn time of M_i is exponentially distributed with rate r_i'. Figure 1 shows a simple AGSPN model with its reachable markings and figure 2 shows reachable graph for a simple AGSPN model.

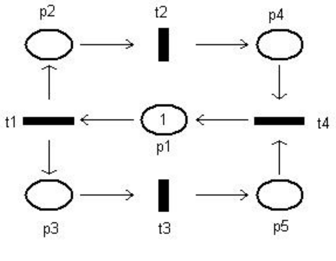

Fig.1. A simple AGSPN model

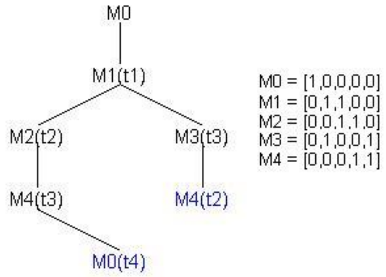

Fig.2. Reachable graph for a simple AGSPN model

The linear system of steady state probabilities is;

$$(\pi_0, \pi_1, \pi_2, \pi_3, \pi_4)\begin{bmatrix} -\lambda_1 & \lambda_1 & 0 & 0 & 0 \\ 0 & -(\lambda_2+\lambda_3) & \lambda_2 & \lambda_3 & 0 \\ 0 & 0 & -\lambda_3 & 0 & \lambda_3 \\ 0 & 0 & 0 & -\lambda_2 & \lambda_2 \\ \lambda_4 & 0 & 0 & 0 & -\lambda_4 \end{bmatrix} = 0$$

$\pi_0 + \pi_1 + \pi_2 + \pi_3 + \pi_4 = 1$. Let Λ = (1 1 1 1 1), then solution to this system is: $\pi_0 = \pi_4 = 2/7$, $\pi_1 = \pi_2 = \pi_3 = 1/7$.

Performance evaluation for AGSPN model

The analysis of an AGSPN model is usually aimed at the computation of more aggregate performance indices than the probabilities of individual markings. Several kinds of aggregate results are easily obtained from the steady state distribution over reachable markings. The probability of an event defined through place markings can be computed by adding the probabilities of all markings in which the condition corresponding to the event definition holds true. The average number of tokens in a place can be obtained by computing the individual probabilities as those of the event "place p_i contains k tokens". The frequency of firing a transition, the average number of times the transition fires in unit time, can be computed as the weighted sum of the transition firing rate:

(5) $$fi = \sum_{i:tj \in E(Mi)} \lambda\, j(Mi) \pi i$$

where f_j is the frequency of firing t_j, E(M_i) is the set of transitions enabled in M_i, and $\lambda_j(M_i)$ is the firing rate of t_j at M_i. The average delay of a token in traversing a subnet in steady state conditions can be computed:

(6) $$E(T) = \frac{E(N)}{E(\gamma)}$$

where E(T) is the average delay, E(N) is the average number of tokens in the process of traversing the subnet, and E(γ) is the average input or output rate of tokens into or out of the subnet [15]. This procedure can be applied whenever the interesting tokens can be identified inside the subnet so that their average number can be computed, and a relation can be established between input and output tokens.

Power transformer fault diagnosis using AGSPN

This paper simulates the actions that are followed by the power transformer maintenance personnel so as to diagnose the fault and repair the power transformer. It is significant to realize that the maintenance personnel cannot know the precise problem from the beginning of the diagnosis process; there is vital information that is attained during the whole power transformer fault diagnosis process. To better model the power transformer fault diagnosis process, AGSPN are used in this paper. These AGSPN supply a structural means, like flow charts, with the additional advantages of simulating dynamic and concurrent actions, and they supply the simulation results using stochastic times for a number of transitions [12]. Figure 3 presents the suggested AGSPN model for power transformer fault diagnosis. Table 1 and table 2 describe all places and transitions that constitute the AGSPN model of figure 3.

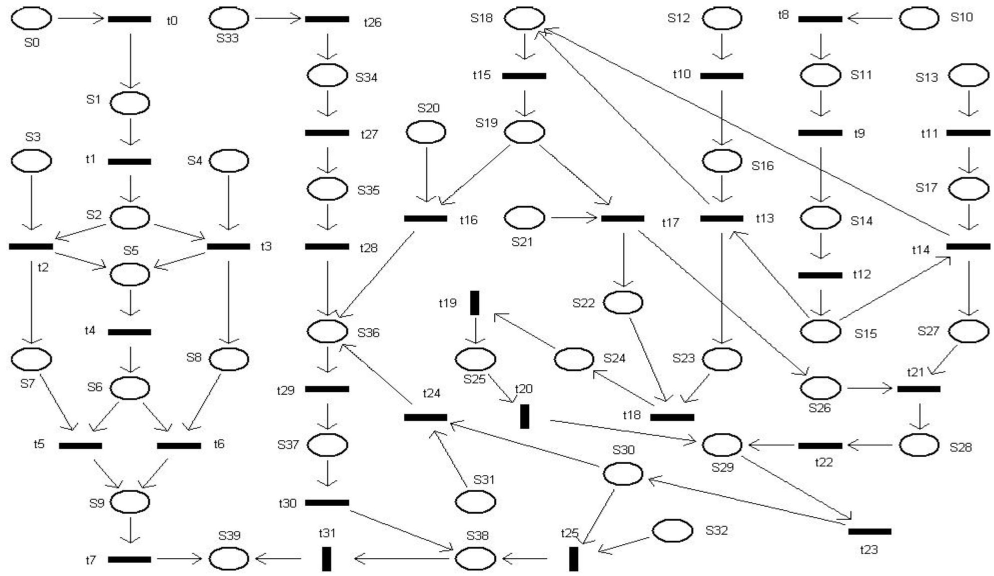

Fig.3. AGSPN model for power transformer fault diagnosis

Places in shadow boxes represent the vital information that is attained during the power transformer fault diagnosis process; these places represent two opposite events, hence tokens can be placed merely in one of the places. The suggested AGSPN models the following power transformer faults: short circuit, overloading, oil leakage and insulation failure. The protection device that is used in a typical distribution power transformer for fault diagnosis is the buchholz relay and the oil thermometer. These protecting schemes may be alarmed or tripped with the appearance of a problem, and when this occurs there is an abrupt warning to the personnel. The probable first warnings are alarm or trip of the buchholz relay and alarm of the oil thermometer. In case of alarm, it can be a make into trip when the maintenance personnel arrive to the power transformer, depending on problem's seriousness and the time required arriving in power transformer's area. There is an overloading problem in the power transformer when the oil thermometer alarms or trips. The maintenance personnel has to check if the loads are over the power transformer overloading limits, diminish the loads accordingly and restart the power transformer. The handling of the maintenance personnel is more complex, in case that the buchholz relay is activated.

Table.1. Description of AGSPN model places

Places	Description
S_0	Thermometer or oil trip
S_1	Staff is notified
S_2	Presence of alarm
S_3	Thermometer or oil alarms
S_4	Thermometer tripped
S_5	Check the loads
S_6	Power transformer need to restart
S_7	Don't restart power transformer
S_8	Power transformer restart
S_9	Loads diminish
S_{10}	Buchholz relay alarm
S_{11}	Staff is notified
S_{12}	Presence of alarm or tripped
S_{13}	Buchholz relay tripped
S_{14}	Buchholz relay still alarm
S_{15}	Low level of oil
S_{16}	Air bubbles in buchholz
S_{17}	Stop power transformer
S_{18}	Presence of oil leakage or insulation failure
S_{19}	Oil leakage
S_{20}	Insulation failure
S_{21}	Check type of fault
S_{22}	Possible repair fault
S_{23}	Don't possible repair fault
S_{24}	Power transformer repair
S_{25}	Possible repair oil leakage
S_{26}	Don't possible repair oil leakage
S_{27}	Staff prepares to repair power transformer
S_{28}	Oil replaced
S_{29}	Possible repair insulation failure
S_{30}	Don't possible repair insulation failure
S_{31}	Replace problematic parts
S_{32}	Check problematic parts
S_{33}	Don't matter changing parts
S_{34}	Power transformer don't work suitable
S_{35}	Power transformer works suitable
S_{36}	Buchholz relay trips
S_{37}	Staff is notified
S_{38}	Identification of fault
S_{39}	Power transformer is disconnected

The probable problems can be insulation failure, short circuit or oil leakage. On the reverse to the activation of the oil thermometer, the first warning of the buchholz relay can be a trip. In this case, the problem is the appearance of a strong short circuit. The repair of the damage cannot be done in the power transformer installation area; the power transformer must be disconnected and transferred in a devoted repairing area. If the first warning of the buchholz relay is alarm, then the maintenance personnel checks. If the relay has been tripped they eventually arrive in the power transformer's area. They also check for the kind of damage. There are two probable contingencies; either the level of the oil indicator is low (S_{15}), or there are air bubbles behind the glass of the buchholz relay (S_{16}). In the first case, the problem is oil leakage, otherwise there is insulation failure. The operation of power transformer stops and it is checked if it is probable to repair the power transformer on site.

Table.2. Description of AGSPN model transitions

Transitions	Description
t_0	Alarm state
t_1	Staff checked station area
t_2	Alarm is still activated
t_3	Trip is activated
t_4	Loads are checked
t_5	Restart is not needed
t_6	Power transformer is restarting
t_7	Loads are diminished sıitable
t_8	Alarm is activated
t_9	Staff checked station area
t_{10}	Trip is activated
t_{11}	Alarm is still activated
t_{12}	Oil level has declined
t_{13}	Air bubbles carry out
t_{14}	Power transformer is stopped
t_{15}	Presence of oil leakage
t_{16}	Presence of insulation failure
t_{17}	Check power transformer
t_{18}	Fault don't repair on the local
t_{19}	Fault repair on the local
t_{20}	Repaire of oil leakage
t_{21}	Power transformer repairs
t_{22}	Oil is replaced
t_{23}	Repair of insulation failure
t_{24}	Problematic parts are replaced
t_{25}	Check power transformer
t_{26}	Fault still occurs
t_{27}	Fault is repaired
t_{28}	Trip is activated
t_{29}	Staff checked station area
t_{30}	Presence of a powerful short circuit
t_{31}	Power transformer is disconnected

This depends on two conditions. The first condition is the type of problem; if the oil leakage is not extensive, the repair can be done or if the insulation failure is on a part outside the tank. The second condition is the presence of appropriate means. The capability of on-site repair enables repairing feasibilities for the two probable problems (S_{25} and S_{29}). The specific type (S_{26} or S_{30}) enables the transition t_{20} or t_{23}. Then the personnel work on the problem. Eventually, there is a check if everything works right. If there is still a problem, then the power transformer must be sent to a devoted repairing area. When the power transformer arrives in the devoted repairing area, before opening the tank, oil has to be removed. Fault diagnosis follows, and next power transformer repair is done. The time needed for power transformer diagnosis and repair is up to many factors, such as availability of spare parts, seriousness of the problem, working load of factory personnel. After repair, the power transformer is reassembled and is filled with oil, and the repaired power transformer passes through quality control tests. If the power transformer passes successfully all the quality control tests, then it is sent back in its area and is reinstalled, otherwise the repairing procedure is repeated.

Conclusion

The PN is a very effective modeling tool for describing and analyzing discrete event dynamic systems. In this paper, AGSPN models provide a powerful modeling tool for representing information and control flows. The power of AGSPN model is their interactive mode which allows a real-time observation and analysis of the system. The most important components of power systems have been modeled in a modular fashion. Power transformer fault diagnosis and repair is a complex task that includes many probable types of faults and demands special trained personnel. A new approach based on AGSPN was suggested for modeling of the power transformers. Tokens in AGSPN model can represent sequential and concurrent execution of several transactions.

PN model of power transformer fault diagnosis is illustrated in detail, especially the characteristics of the model. This approach provides the possibility of hierarchically monitoring of power transformer. The deduction procedure can be presented graphically in the form of AGSPN. From this review on, it is clear that much research work has been done on the applications of the PN in solving many power transformer problems. However, most of the research work in this area is based on very small sample power transformer faults, and is hence very preliminary. Particularly, up to now no practical applications have been reported. Applications of the AGSPN to solve problems in complex power transformer faults. Simulation results for the most common types of power transformer faults; oil leakage, overloading, insulation failure and short circuit are presented. The proposed methodology objectives at identifying the power transformer fault and estimating the duration for power transformer repair. This model is good for the fault diagnosis of power transformer. It shows that the fault diagnosis system based on the proposed models is practicable and effective.

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