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A Systematic Stochastic Petri Net Based Methodology for Transformer Fault Diagnosis and Repair Actions

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Abstract Transformer fault diagnosis and repair is a complex task that includes many possible types of faults and demands special trained personnel. Moreover, the minimization of the time needed for transformer fault diagnosis and repair is an important task for electric utilities, especially in cases where the continuity of supply is crucial. In this paper, Stochastic Petri Nets are used for the simulation of the fault diagnosis process of oil-immersed transformers and the definition of the actions followed to repair the transformer. Transformer fault detection is realized using an integrated safety detector, in case of sealed type transformer that is completely filled with oil, while a Buchholz relay and an oil thermometer are used, in case of transformer with conservator tank. Simulation results for the most common types of transformer faults (overloading, oil leakage, short-circuit and insulation failure) are presented. The proposed Stochastic Petri Net based methodology provides a systematical determination of the sequence of fault diagnosis and repair actions and aims at identifying the transformer fault and estimating the duration for transformer repair.

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1. Introduction

The process of electric utilities restructuring, privatization and deregulation has created a competitive, global marketplace for energy [1]. Early preparation to market competition and best use of technology will drive success in this new and challenging environment. Twenty-first century utilities will try to further improve system reliability and quality, while simultaneously being cost effective.

Power system reliability depends on component reliability. As the ultimate element in the electricity supply chain, the power transformer is one of the most widespread apparatus in electric power systems. During their operation, transformers are subjected to many external electrical stresses from both the upstream and downstream network. The consequences of transformer fault can be significant (damage, oil pollution, etc). Transformers must, therefore, be protected against attacks of external origin, and be isolated from the network in case of internal failure.

It is the electrical network designer's responsibility to define the measures to be implemented for each transformer as a function of criteria like continuity and quality of service, cost of investment and operation and safety of property and people as well as the acceptable level of risk. The solution chosen is always a compromise between the various criteria and it is important that the strengths and weaknesses of the chosen compromise are clearly identified [2]. The high reliability level of transformers is a decisive factor in the protection choices that are made by electrical utilities, faced with the unit cost of the protection devices that can be associated with them.

In spite of the high reliability of transformers, in practice, various types of faults (e.g. insulation failure, overloading, oil leakage, short-circuit, etc) can occur to the transformers of an electrical utility. Failure of these transformers is very costly to both the electrical companies and their customers.

When a transformer fault occurs, it is important to identify the fault type and to minimize the time needed for transformer repair, especially in cases where the continuity of supply is crucial. Consequently, it should not come as a surprise that transformer fault diagnosis forms a subject of a permanent research effort.

Various transformer fault diagnosis techniques have been proposed in the literature, for different types of faults [3]. For thermal related faults, the most important diagnostic method is the gas-in-oil analysis [4, 5], while other methods such as the degree of polymerization, the furanic compounds analysis and the thermography are also applicable [6]. For dielectric related faults, it is necessary to localize and to characterize the partial discharge source, in order to give a correct diagnosis after receiving an alarm signal via sensors or via gas-in-oil sampling [7]. For mechanical related faults, the frequency response analysis and the leakage inductance methods are the more frequently used transformer fault diagnosis techniques [8]. Finally, for transformer general degradation, the dielectric response, the oil analysis and the furanic compounds analysis methods are applicable [9].

In spite of the wide range of the transformer fault diagnosis methods, the diagnostic criteria developed till today are not fully applicable to all faulty cases, and consequently, the experience of experts still play an important role in the diagnosis of the transformer faults. Dismantling the suspected transformers, performing internal examinations, and holding a group discussion are usually the procedure to conclude the diagnosis.

Expert systems and artificial intelligence techniques have already been proposed to understand the obvious and non-obvious relationships between transformer failures and the causes of failures (i.e. internal or external causes) [10–13]. Preliminary results, obtained 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 [14].

Petri Nets and their modifications and extensions including Stochastic Petri Nets are both a mathematical and graphical tool capable of capturing deterministic or stochastic system behavior and modeling phenomena such as sequentialism, parallelism, asynchronous behavior, conflicts, resource sharing and mutual exclusion [15]; further, Stochastic Petri Nets do simulate rather accurately dynamic and concurrent system operations – actions using stochastic times associated with pertinent transitions.

In this paper, Stochastic Petri Nets are proposed for modeling of fault diagnosis process of oil-immersed transformers with conservator tank as well as for sealed type transformers, which are completely filled with oil. The proposed methodology offers significant advantages such as systematical determination of the sequence of fault diagnosis and repair actions, visual representation of the above actions, as well as estimation of the time needed for transformer repair. The novelty of using Petri Nets (PNs) is in fact that the PN is both a graphical and mathematical tool. One can view the sequence of events in transformer fault diagnosis, and at the same time, through the reachability graph the state transitions of the system (dynamic). Further, through the reachability graph one can determine potential deadlocks, etc.

The paper is organized as follows: Section 2 briefly describes the Petri Nets methodology. The application of Stochastic Petri Nets to transformer fault diagnosis and the obtained results are described in Section 3. Section 4 concludes the paper.

2. Overview of Petri Nets

2.1. Ordinary Petri Nets

An Ordinary Petri Net (*OPN*) is a bipartite directed graph defined as the five-tuple: $PN = \{P, T, I, O, m_0\}$, where $P = \{p_1, p_2 \dots p_{np}\}$ is a finite set of places, $T = \{t_1, t_2 \dots t_{nt}\}$ is a finite set of transitions, $P \cup T = V$, where V is the set of vertices and $P \cap T = \emptyset$. I: $(P \times T) \rightarrow N$ is an input function and O: $(P \times T) \rightarrow N$ an output function with N a set of non-negative integers, and m_0 the *PN* initial marking. Places represent conditions; transitions represent events and arcs direct connection, access rights or logical connection between places and transitions.

Places are used to describe possible local system rates, named conditions or situations. Transitions are used to describe events that may modify the system state. Arcs specify the relation between local states and events in two ways: They indicate the local state in which the event can occur, and the local state transformations induced by the event.

PN structural and behavioral properties (*reachability*, *coverability*, *safeness*, *k-boundedness*, *conflicts*, *liveness*, *reversibility*, *persistency*, *deadlock-freeness*, *P-* and

T- invariants) capture precedence relations and structural interactions between system components. Behavioral properties depend on, and are coupled with, the *PN* initial marking m_0. Structural properties are determined using the *PN* topological structure following matrix-based analysis methods [15–17].

The incidence matrix A for a *PN* consisting of n_p places and n_t transitions is defined as $A = [a_{ij}]$, where $a_{ij} = a_{ij}^{+} - a_{ij}^{-}$; $a_{ij}^{+} = w\ (i, j)$ is the arc weight from transition i to its output place j and $a_{ij}^{-} = w(j, i)$ is the arc weight to transition i from its input place j. a_{ij}^{+}, a_{ij}^{-} and a_{ij} represent the tokens added, removed and totally changed in a place j by the firing of transition i, respectively. The incidence matrix cannot represent self-loops (since the total difference of tokens in a self loop is equal to zero).

The incidence matrix is used for the invariants calculation. Given a *PN*, there exists *place* or *P-invariants* and *transition* or *T-invariants*. *P-invariants* are the nonzero nonnegative integer solutions X of the matrix equation $X^T A = 0$ that also satisfy $X^T m = X^T m_0$ where X is an n_p-element vector, m_0 the initial marking of the net and m a marking that belongs to the reachability set of m_0 , $R(m_0\ )$. *T-invariants* are the nonzero nonnegative integer solutions Y of the matrix equation $AY = 0$ where Y is an n_t-element vector. There are $(n_p - r)$ basic *P-invariants* and $(n_t - r)$ *T-invariants*, where $r = rank(A)$. *P-invariants* express a notion of token conservation in sets of places for all reachable markings without enumeration of the reachability set $R(m_0)$. *T- invariants* describe a transition firing sequence S, such that $m_j \rightarrow m_j$. In consequence, any cyclic repetitive sequence of marking changes of a system represented by a *PN* is a *T-invariant*.

Since any linear combination of two or more *P*-(*T*-) invariants is also a *P*-(*T*-) *invariant*, only the sets of basic (or minimal) invariants are of interest and are calculated [18]. The Martinez and Silva algorithm [19] may be utilized to determine net invariants by removing consecutive net elements.

2.2. Timed Petri Nets

For problems that include the completion of an activity, it is necessary and useful to introduce the duration of activities into the PN model. Time can be associated with both nodes (places or transitions), but Timed Petri Net (TPN) models analysis is simpler when time is attached to one kind of nodes [20]. The case described is that of PNs where time is attached to transitions, called *t*-timed Petri nets.

A *t*-timed PN arises from the corresponding Ordinary PN by associating each transition t_i a firing delay that may be constant or follow a given distribution. A TPN is defined by the tuple $TPN = \{P, T, I, O, m_0, D\}$, such that the first five elements are as described above for ordinary PNs while D represents time delay and is a function from the set of non-negative real numbers $\{0, R^{+}\}$. $D(t_i)$ is a vector whose number of elements is the same with the number of net's transitions, where d_i is the delay associated with transition i. A timed transition's firing consists of two events namely, 'start firing' and 'end firing'. In between these two events the firing is in progress. Tokens are removed from input places at 'start firing' and are deposited to output places at 'end of firing' [21]. The transitions delays may be deterministic or described by a distribution. In TPNs some transitions may have zero occurrence times and are called 'immediate'.

2.3. Stochastic Petri Nets

The Stochastic Petri Nets (SPN) considered here are ordinary Petri nets in which the firings of some transitions need certain amounts of time. This means that SPNs have three different types of transitions: Immediate, deterministic and stochastic transitions. The immediate transitions have zero occurrence times (their firing is immediate). In the deterministic transitions, the time delays for the firing of the transitions are deterministically given (in this paper, the delays of the deterministic transitions are integer positive numbers). In the stochastic transitions, the time delays from enabling to the firing of the transitions are associated with random variables that are probabilistically specified (in this paper, uniform and exponential distribution have been considered).

The Stochastic Petri Net model provides a more realistic representation of matter [22], for problems that include the completion of an activity (such problem is the transformer fault diagnosis and repair process).

2.4. Petri Net Applications

Petri Nets and their extensions being both a mathematical and graphical tool are widely used for modeling discrete event dynamic systems including production systems and networks [16, 23–25]. PNs have been proven to be a powerful tool for studying system concurrency, sequential, parallel, asynchronous, distributed deterministic or stochastic behavior, resource allocation, mutual exclusion and conflicts [16, 17, 26].

In Power Systems, Petri Nets have been applied to the areas of fault diagnosis [27], power system restoration [28–30], sequence and process control [31–35], computer-based automatic control design in substations [36, 37], fault section estimation [38] and reliability evaluation [39].

3. Fault Diagnosis with Petri Nets

3.1. Objectives

This paper simulates the actions that are followed by the electric utility transformer maintenance personnel in order to diagnose the fault and repair the transformer. It is important to notice that the maintenance staff is not able to know the exact problem from the beginning of the diagnosis process; there is crucial information that is obtained during the whole transformer fault diagnosis process.

The main objective of the paper is to provide a methodology that will help the electric utility maintenance staff to repair the transformer on-site, when this is feasible (e.g. if the damage is not inside the transformer; see Sections 3.3 and 3.4). If the damage is inside the transformer, the electric utility maintenance staff is not able to repair on-site the transformer, which is sent in a dedicated repairing area (e.g. in a transformer factory). In the latter case, it is important for the electric utility to have an estimate for the duration of the transformer repair.

3.2. Methodology

To better model the transformer fault diagnosis process, Stochastic Petri Nets are used in this paper. These nets provide a structural tool, like flow charts, with the additional advantages of simulating dynamic and concurrent actions, and they provide the simulation results using stochastic times for a number of transitions.

Transformer fault diagnosis is linked with transformer fault detection, which depends on the type of transformer (with conservator tank or sealed type completely filled with oil), and the fault detection equipment that is used. In this paper, two different transformer fault detection schemes are considered. In the first scheme, the fault detection is realized using a Buchholz relay and an oil thermometer for an oil-immersed transformer with conservator tank, while in the second scheme, an integrated safety detector implements fault detection for a sealed type transformer, which is completely filled with oil. In both schemes, the proposed PN models the following transformer faults: Overloading, short-circuit, insulation failure and oil leakage.

3.3. Transformer with Conservator Tank

The protection equipment that is commonly used for fault detection in a typical power transformer with conservator tank is the oil thermometer and the Buchholz relay. These protecting schemes may be alarmed or tripped with the appearance of a problem, and when this happens there is an immediate warning to the personnel. The possible initial warnings are a) alarm of the oil thermometer (oil thermometer cannot trip without earlier alarm), and b) alarm or trip of the Buchholz relay. In case of alarm, it can be a change to trip when the maintenance staff arrives to the transformer, depending on problem's seriousness and the time required arriving in transformer's area.

When the oil thermometer alarms or trips, there is an overloading problem in the transformer. The maintenance staff has to check if the loads are over the transformer overloading limits, reduce the loads accordingly and restarts the transformer (in case of trip).

The handling of the maintenance staff is more complex, in case that the Buchholz relay is activated. The possible problems can be short-circuit, insulation failure or oil leakage. On the contrary to the activation of the oil thermometer, the initial 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 transformer installation area; the transformer must be disconnected and transferred in a dedicated repairing area (e.g. in a transformer factory).

Figure 1 presents the proposed PN model for transformer fault diagnosis, Figure 2 shows the 'not on-site repair' subnet (i.e. in case that the transformer repair is implemented in the factory), and Table I describes all places and transitions that constitute the PN models of Figures 1 and 2. Places in shadow boxes represent the crucial information that is obtained during the transformer fault diagnosis process; these places represent two opposite events, so tokens can be placed only in one of the places.

If the initial warning of the Buchholz relay is alarm, then the maintenance staff checks if the relay has been tripped, when they finally arrive in the transformer's area.

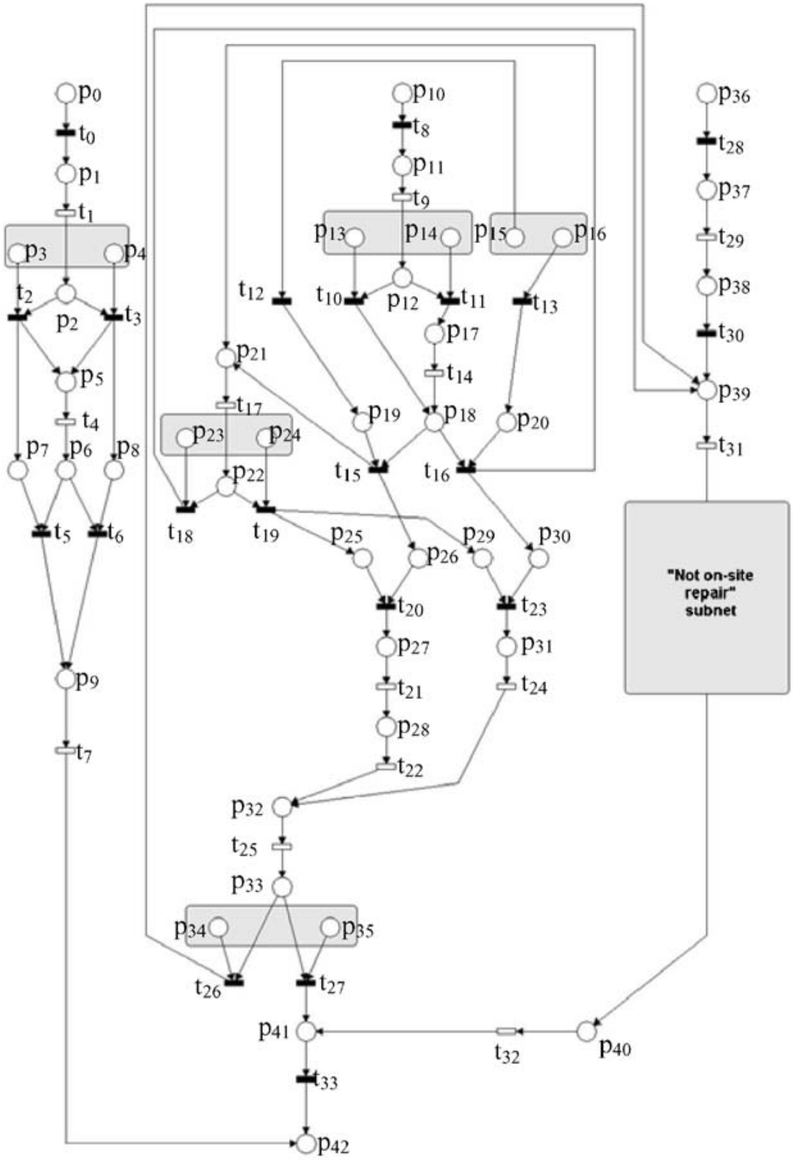
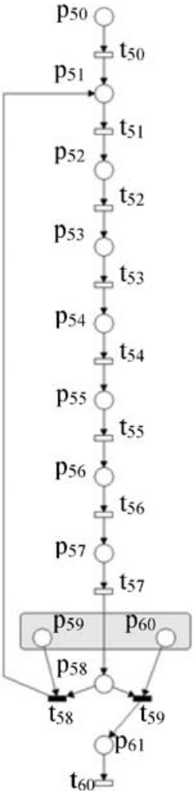


Figure 1 Petri Net based fault diagnosis model for transformer with conservator tank.

They also check for the kind of damage. There are two possible contingencies: Either the level of the oil indicator is low (p_{15}), or there are air bubbles behind the glass of the Buchholz relay (p_{16}). In the first case, the problem is oil leakage; otherwise there is insulation failure. The operation of transformer stops (in case of alarm) and it is checked if it is possible to repair the transformer on site. This depends on a) the type of problem: The repair can be done if the oil leakage is not wide (i.e. the size

Figure 2 Petri Net based fault diagnosis model for transformer “not on-site repair”.



of hole in the tank is very small) or if the insulation failure is on a part outside the tank, and b) the existence of suitable tools. The capability of on site repair enables repairing possibilities for the two possible problems (p_{25} and p_{29}) and the specific type (p_{26} or p_{30}) enables the transition t_{20} or t_{23}. Then the staff works on the problem (in the case of oil leakage, the lost oil has also to be replaced). Finally, there is a check if everything works right. If there is still a problem, then the transformer must be sent to a dedicated repairing area (i.e. on site repair is not possible). The ‘not on-site repair’ subnet of Figure 2 is then models the transformer fault diagnosis and repair process.

When the transformer arrives in the dedicated repairing area (not on site repair), before opening the tank, oil has to be removed. Fault diagnosis follows, and next transformer repair is done. The time needed for transformer diagnosis and repair depends on many factors, such as seriousness of the problem, availability of spare parts, working load of factory personnel, etc. After repair, the transformer is reassembled and is filled with oil, and the repaired transformer passes through quality control tests. If the transformer passes successfully all the quality control tests, then it is sent back in its area and is reinstalled (see Figure 1), otherwise the repairing procedure is repeated.

By using the reachability graph, it can be shown that the net is live, safe and reversible. The existence of these important PN properties within the frame of the

Table I Description of Petri Net places and transitions (transformer with conservator tank)

Main Petri net	
p_0	Oil thermometer alarms
t_0	Alarm is activated
p_1	Personnel is notified
t_1	Personnel is moving to transformer area
p_2	Existence of alarm or trip?
p_3	Oil thermometer still alarms
t_2	Alarm is still activated
p_4	Oil thermometer tripped
t_3	Trip is activated
p_5	Need to check the loads
t_4	Loads are checked
p_6	Does transformer need to restart?
p_7	It doesn't need to restart
t_5	No restart is needed
p_8	It needs to restart
t_6	Transformer is restarting
p_9	Loads have to be reduced properly
t_7	Loads are reduced properly
p_{10}	Buchholz relay alarms
t_8	Alarm is activated
p_{11}	Personnel is notified
t_9	Personnel is moving to transformer area
p_{12}	Existence of alarm or trip?
p_{13}	Buchholz relay tripped
t_{10}	Trip is activated
p_{14}	Buchholz relay still alarms
t_{11}	Alarm is still activated
p_{15}	Low level of oil indicator
t_{12}	Oil volume has reduced
p_{16}	Air bubbles in Buchholz relay's glass
t_{13}	Air bubbles are observed
p_{17}	Transformer needs to stop
t_{14}	Transformer is stopped
p_{18}	Existence of oil leakage or insulation failure?
p_{19}	Oil leakage
t_{15}	Existence of oil leakage
p_{20}	Insulation failure
t_{16}	Existence of insulation failure
p_{21}	Check for the exact type of fault
t_{17}	Transformer is checked
p_{22}	Is it possible repair fault on the spot?
p_{23}	It is not possible to repair
t_{18}	Fault cannot be repaired on the spot
p_{24}	It is possible to repair
t_{19}	Fault can be repaired on the spot
p_{25}	Possibility for repairing oil leakage
p_{26}	Problem of oil leakage
t_{20}	Repair of oil leakage is possible
p_{27}	Personnel prepares to repair transformer
t_{21}	Transformer is repaired

Table I Continued.

p_{28}	Lost oil needs to be replaced
t_{22}	Lost oil is replaced
p_{29}	Possibility for repairing insulation failure
p_{30}	Problem of insulation failure
t_{23}	Repair of insulation failure is possible
p_{31}	Need to replace problematic external parts
t_{24}	Parts are replaced
p_{32}	Check if everything works properly
t_{25}	Transformer is checked
p_{33}	Is transformer working properly?
p_{34}	It is not working properly
t_{26}	Fault still exists
p_{35}	It is working properly
t_{27}	Fault is repaired
p_{36}	Buchholz relay trips
t_{28}	Trip is activated
p_{37}	Personnel is notified
t_{29}	Personnel is moving to transformer area
p_{38}	Identification of transformer's fault
t_{30}	Existence of a powerful short-circuit
p_{39}	Transformer needs to disconnect
t_{31}	Transformer is disconnected
p_{40}	Transformer arrives in area of installation
t_{32}	Transformer is reinstalled
p_{41}	Transformer is ready to work
t_{33}	Transformer is restarted
p_{42}	Transformer reworks properly
'Not on-site repair' subnet	
p_{50}	Transformer is being sent to repairing area
t_{50}	Transformer arrives to repairing area
p_{51}	Oil has to be removed
t_{51}	Oil is removed
p_{52}	Inside search is needed
t_{52}	Tank is opened
p_{53}	Check for the exact type of fault
t_{53}	Check is done
p_{54}	Identification of fault
t_{54}	Fault is repaired
p_{55}	Transformer has to be reassembled
t_{55}	Transformer is reassembled
p_{56}	Oil has to be added
t_{56}	Oil is added
p_{57}	Check for the proper operation
t_{57}	Check is done
p_{58}	Is transformer working properly?
p_{59}	It is not working properly
t_{58}	Fault still exists
p_{60}	It is working properly
t_{59}	Fault is repaired
p_{61}	Transformer is ready to be sent back in its area
t_{60}	Transformer is transferred

transformer fault diagnosis and repair process assures that the proposed sequence of diagnosis and repair actions are feasible.

Considering the sequence of transition firings and all marking reachable from the initial marking, the reachability graph of the Petri subnet of Figure 2 is drawn in Figure 3 for the case of non-existence of any fault after the repair. The dotted arc represents the modification carried out on the individual subnet, in order to validate its properties. By examining this reachability graph [15, 17], it is validated that the constructed model is safe, live and reversible. Safeness ensures that the simulation of our Petri Net represents the real operation, while the presence of a second token in a place could lead us to misleading results about the state of the system and consequently to wrong repairing actions. Liveness secures that our Petri Net does not stop its simulation (operation) in a non-desirable state. Reachability ensures the proper sequence of actions for repairing transformer faults. The verification of these important PN properties assures that our subnet is feasible and deadlock-free [23].

In the proposed PN modeling, immediate, deterministic and stochastic transitions are used, which take integer values that represent hours. For stochastic transitions, uniform distribution is assumed (i.e. the duration for transition t_7 of main net: Loads are properly reduced, can take an integer value from interval [1 3]). The duration of the transitions depends on the electric utility as well as the manufacturing plant that is in charge for the 'not on-site repair' of the transformer. The stochastic characteristics of the PN, type of distribution and transition durations, are determined based on prior knowledge on transformer fault diagnosis. This knowledge has been collected after discussions with experts in transformer fault diagnosis and repair. These experts are coming from the electric utility (area of expertise: On-site repair) and the transformer

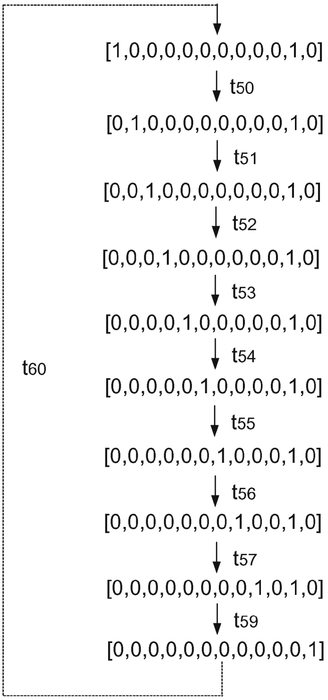


Figure 3 Reachability graph of the PN model of Figure 2.

manufacturer (area of expertise: ‘Not on-site repair’). The PN model ‘captures’ such profiles during simulation/execution. The PN does not change, if the profile of the random variable changes. Tables II and III present indicative values for the duration of the transitions of the main petri net and the ‘not on-site repair’ subnet, respectively. In Tables II and III, the duration of the immediate transitions is zero hours, the duration of the deterministic transitions is a positive integer number of hours, and the duration of the stochastic transitions can take an integer value of hours from the interval that is specified by two integer numbers into square brackets. Table IV presents the simulation results for fault diagnosis and repair using the main Petri Net and the ‘not on-site repair’ subnet models as well as the duration of the transitions shown in Tables II and III. For the calculation of the simulation results, a set of 100 simulations has been considered, using the HPSIM Petri Net simulator [40].

Table II Duration of the transitions of the main Petri Net (transformer with conservator tank)

Transition	Description	Duration (hours)
t_0	Alarm is activated	0
t_1	Personnel is moving to transformer area	[0 2]
t_2	Alarm is still activated	0
t_3	Trip is activated	0
t_4	Loads are checked	[1 5]
t_5	No restart is needed	0
t_6	Transformer is restarting	0
t_7	Loads are reduced properly	[1 3]
t_8	Alarm is activated	0
t_9	Personnel is moving to transformer area	[0 2]
t_{10}	Trip is activated	0
t_{11}	Alarm is still activated	0
t_{12}	Oil volume has reduced	0
t_{13}	Air bubbles are observed	0
t_{14}	Transformer is stopped	1
t_{15}	Existence of oil leakage	0
t_{16}	Existence of insulation failure	0
t_{17}	Transformer is checked	1
t_{18}	Fault cannot be repaired on the spot	0
t_{19}	Fault can be repaired on the spot	0
t_{20}	Repair of oil leakage is possible	0
t_{21}	Transformer is repaired	[2 5]
t_{22}	Lost oil is replaced	1
t_{23}	Repair of insulation failure is possible	0
t_{24}	Parts are replaced	2
t_{25}	Transformer is checked	1
t_{26}	Fault still exists	0
t_{27}	Fault is repaired	0
t_{28}	Trip is activated	0
t_{29}	Personnel is moving to transformer area	[0 2]
t_{30}	Existence of a powerful short-circuit	0
t_{31}	Transformer is disconnected	2
t_{32}	Transformer is reinstalled	2
t_{33}	Transformer is restarted	0

Table III Duration of the transitions of the 'not on-site repair' subnet

Transition	Description	Duration (hours)
t_{50}	Transformer arrives to repairing area	[2 24]
t_{51}	Oil is removed	1
t_{52}	Tank is opened	1
t_{53}	Check is done	1
t_{54}	Fault is repaired	[72 360]
t_{55}	Transformer is reassembled	1
t_{56}	Oil is added	4
t_{57}	Check is done	1
t_{58}	Fault still exists	0
t_{59}	Fault is repaired	0
t_{60}	Transformer is transferred	[2 4]

The duration of the simulation that reaches more the mean value of the set of 100 simulations has been chosen and presented in Table IV. The heavy impact of the 'not on-site repair' on the duration of the transformer repair is obvious, when analyzing the results of Table IV.

To simulate better the durations of transformer repairing for a number of alternative companies in the marketplace, a second approach was followed, in which a modification in the type of distribution (from uniform to exponential) for a number of stochastic transitions was considered. The distribution of the changed transitions is presented in Table V, while the new simulation results are presented in Table VI.

3.4. Sealed Type Transformer

The protection equipment that is commonly used for fault detection in a typical sealed type power transformer, which is completely filled with oil, is an integrated safety detector. This device contains four switches: A pressure switch, which trips the transformer operation in case of a strong short-circuit; a thermostat switch which alarms when oil temperature exceeds a predetermined temperature level; another thermostat switch that stops the transformer operation when oil temperature reaches the trip level; and an alarm switch that operates when oil is reduced to a specified level. The last switch also protects the transformer from an insulation failure, as the generated bubbles reduce the oil level. The activation of the above switches

Table IV Simulation results for transformer with conservator tank

Fault	Duration (hours)
Oil leakage (without trip)	8
Oil leakage (not on-site repair)	159
Overloading	4
Insulation failure (bushings, without trip)	6
Insulation failure (not on-site repair)	258
Short-circuit (not on-site repair)	275

Table V Duration of the modified transitions of the second approach (transformer with conservator tank)

Transition	Description	Duration (hours)
t_1, t_9, t_{29}	Personnel is moving to transformer area	Exp(1)
t_{50}	Transformer arrives to repairing area	Exp(12)
t_{54}	Fault is repaired	Exp(180)
t_{60}	Transformer is transferred	Exp(2)

notifies directly the personnel, and makes it capable of realizing the general type of the problem.

Figure 4 presents the proposed PN model for transformer fault diagnosis and Table VII describes all places and transitions that constitute the PN model of Figure 4.

The possible initial warnings are a) alarm of the thermostat switch (thermostat switch cannot trip without earlier alarm), b) trip of the pressure switch, and c) alarm of the oil level detector. In case of thermostat switch alarm, it can be a change to trip when the maintenance staff arrives to the transformer, depending on problem's seriousness and the time required arriving in transformer's area.

When the alarm or trip thermostat switch is activated, there is an overloading problem in the transformer. The maintenance staff has to check if the loads are over the transformer overloading limits, reduce the loads accordingly and restarts the transformer (in case of trip).

If the pressure's switch trips, the problem is the appearance of a strong short-circuit. The repair of the damage cannot be done in the transformer installation area; the transformer must be disconnected and transferred in a dedicated repairing area (e.g. in a transformer factory).

The handling of the maintenance staff is more complex, in case of alarm of the oil level detector. The possible problems can be oil leakage or insulation failure. Initially, the maintenance staff has to check the exact kind of damage. There are two possible contingencies: Either the level of the oil indicator is low (p_{12}), or there are air bubbles behind the observation glass (p_{13}). In the first case, the problem is oil leakage; otherwise there is insulation failure. The operation of transformer has to stop and it is checked if it is possible to repair it on-site. This depends on a) the type of problem: The repair can be done if the oil leakage is not wide (i.e. the size of hole in the tank is very small) or if the insulation failure is on a part outside the tank, and b) the existence of suitable tools.

Table VI Simulation results for transformer with conservator tank (second approach)

Fault	Duration (hours)
Oil leakage (without trip)	8
Oil leakage (not on-site repair)	211
Overloading	4
Insulation failure (bushings, without trip)	6
Insulation failure (not on-site repair)	212
Short-circuit (not on-site repair)	205

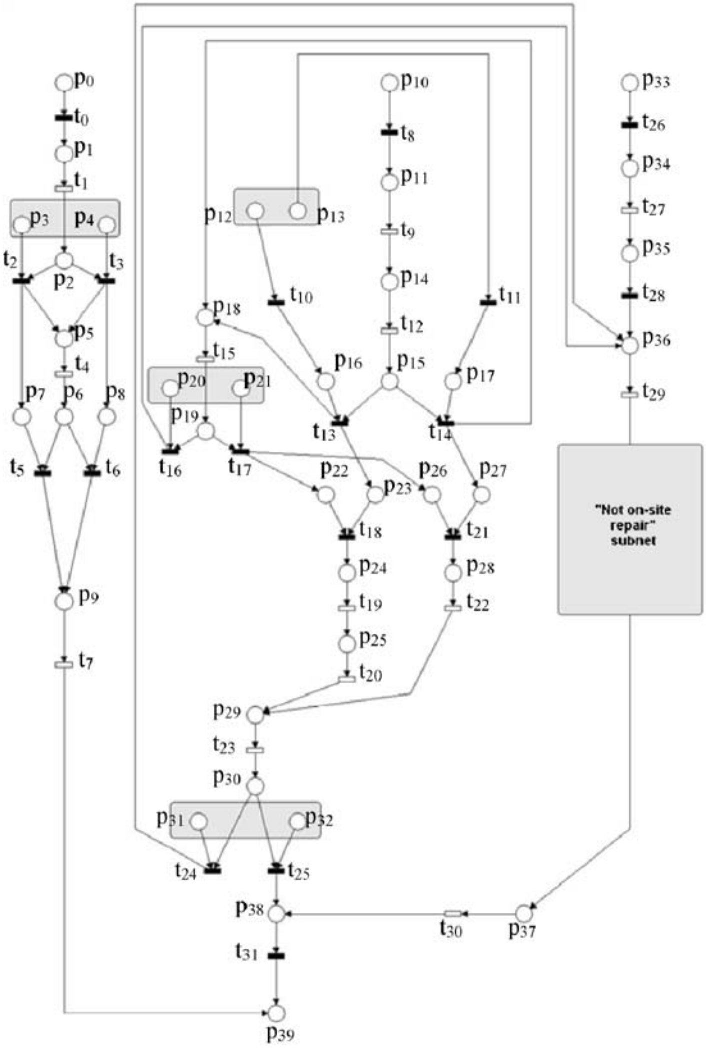


Figure 4 Petri Net based fault diagnosis model for sealed type transformer.

The capability of on-site repair enables repairing possibilities for the two possible problems (p_{22} and p_{26}) and the specific type (p_{23} or p_{27}) enables the transition t_{18} or t_{21} (on-site repair of the damage is possible). Then the staff works on the problem (in the case of oil leakage, the lost oil has also to be replaced). Finally, there is a check if everything works right. If there is still a problem, then the transformer must be sent to a dedicated repairing area (i.e. on-site repair is not possible). The 'not on-site repair' subnet of Figure 2 then models the transformer fault diagnosis and repair process.

Following the procedure described in Section 3.3, Table VIII presents the durations that are assigned to the transitions of the Petri Net of Figure 4, while for the duration of the transitions of the 'not on-site repair' subnet, the values of Table III are used. Table IX presents the simulation results for fault diagnosis and repair.

Table VII Description of places and transitions of Petri Net of sealed type transformer

p_0	Thermostat switch alarms
t_0	Alarm is activated
p_1	Personnel is notified
t_1	Personnel is moving to transformer area
p_2	Existence of alarm or trip?
p_3	Thermostat switch still alarms
t_2	Alarm is still activated
p_4	Thermostat switch tripped
t_3	Trip is activated
p_5	Need to check the loads
t_4	Loads are checked
p_6	Does transformer need to restart?
p_7	It doesn't need to restart
t_5	No restart is needed
p_8	It needs to restart
t_6	Transformer is restarting
p_9	Loads have to be reduced properly
t_7	Loads are reduced properly
p_{10}	Oil level detector alarms
t_8	Alarm is activated
p_{11}	Personnel is notified
t_9	Personnel is moving to transformer area
p_{12}	Low level of oil indicator
t_{10}	Oil volume has reduced
p_{13}	Air bubbles in oil indicator' s glass
t_{11}	Air bubbles are observed
p_{14}	Transformer needs to stop
t_{12}	Transformer is stopped
p_{15}	Existence of oil leakage or insulation failure?
p_{16}	Oil leakage
t_{13}	Existence of oil leakage
p_{17}	Insulation failure
t_{14}	Existence of insulation failure
p_{18}	Check for the exact type of fault
t_{15}	Transformer is checked
p_{19}	Is it possible repair fault on the spot?
p_{20}	It is not possible to repair
t_{16}	Fault cannot be repaired on the spot
p_{21}	It is possible to repair
t_{17}	Fault can be repaired on the spot
p_{22}	Possibility for repairing oil leakage
p_{23}	Problem of oil leakage
t_{18}	Repair of oil leakage is possible
p_{24}	Personnel prepares to repair transformer
t_{19}	Transformer is repaired
p_{25}	Lost oil needs to be replaced
t_{20}	Lost oil is replaced
p_{26}	Possibility for repairing insulation failure
p_{27}	Problem of insulation failure
t_{21}	Repair of insulation failure is possible
p_{28}	Need to replace problematic external parts

Table VII Continued.

t_{22}	Parts are replaced
p_{29}	Check if everything works properly
t_{23}	Transformer is checked
p_{30}	Is transformer working properly?
p_{31}	It is not working properly
t_{24}	Fault still exists
p_{32}	It is working properly
t_{25}	Fault is repaired
p_{33}	Pressure switch trips
t_{26}	Trip is activated
p_{34}	Personnel is notified
t_{27}	Personnel is moving to transformer area
p_{35}	Identification of transformer's fault
t_{28}	Existence of a powerful short-circuit
p_{36}	Transformer needs to disconnect
t_{29}	Transformer is disconnected
p_{37}	Transformer arrives in area of installation
t_{30}	Transformer is reinstalled
p_{38}	Transformer is ready to work
t_{31}	Transformer is restarted
p_{39}	Transformer reworks properly

In sealed type transformer, the second approach described in Section 3.3 is also followed. Table X presents the distribution type of the modified transitions, while Table XI presents the new simulation results. It is seen that the duration of the fault diagnosis and repair is the same for both scenarios as in the case of the transformer with conservator tank.

3.5. Comments

The PN approach represents an efficient, interactive, graphical modeling and analysis tool for transformer fault diagnosis and repair providing a) easy visualization of the current status of transformer diagnosis and repair, b) simulation of the dynamic behavior of the transformer during diagnosis and repair (e.g. Buchholz relay still alarms) by the flow of tokens exploring the analysis techniques of reachability graph [15, 17].

The PNs have definite advantages over conventional representation tools, like flow charts. Namely, PNs can capture the dynamic behavior of the transformer fault diagnosis and repair through the flow of tokens, while a flow chart is simply a static visualization of the system profile. In addition, net's structural properties can be proved taking advantage of the mathematical background of PN theory, properties essential for the deadlock-free operation of the modeled system.

Of primary importance is the fact that the proposed PN methodology provides generic transformer fault diagnosis and repair guidelines rather than system-dependent. These general guidelines can be easily customized to each utility's transformer fault diagnosis and repair strategy and be applied on specific facts. In that sense, the proposed framework can serve as generic tool applicable to several scenarios and policies.

Table VIII Duration of the transitions of the main Petri Net (sealed type transformer)

Transition	Description	Duration (hours)
t_0	Alarm is activated	0
t_1	Personnel is moving to transformer area	[0 2]
t_2	Alarm is still activated	0
t_3	Trip is activated	0
t_4	Loads are checked	[1 5]
t_5	No restart is needed	0
t_6	Transformer is restarting	0
t_7	Loads are reduced properly	[1 3]
t_8	Alarm is activated	0
t_9	Personnel is moving to transformer area	[0 2]
t_{10}	Oil volume has reduced	0
t_{11}	Air bubbles are observed	0
t_{12}	Transformer is stopped	1
t_{13}	Existence of oil leakage	0
t_{14}	Existence of insulation failure	0
t_{15}	Transformer is checked	1
t_{16}	Fault cannot be repaired on the spot	0
t_{17}	Fault can be repaired on the spot	0
t_{18}	Repair of oil leakage is possible	0
t_{19}	Transformer is repaired	[2 5]
t_{20}	Lost oil is replaced	1
t_{21}	Repair of insulation failure is possible	0
t_{22}	Parts are replaced	2
t_{23}	Transformer is checked	1
t_{24}	Fault still exists	0
t_{25}	Fault is repaired	0
t_{26}	Trip is activated	0
t_{27}	Personnel is moving to transformer area	[0 2]
t_{28}	Existence of a powerful short-circuit	0
t_{29}	Transformer is disconnected	2
t_{30}	Transformer is reinstalled	2
t_{31}	Transformer is restarted	0

3.6. Future Work

On-going work concerns the development of a software environment that will make use of the above PN models and at the same time will be able to interchange data and results with transformer fault diagnosis and repair databases. These databases

Table IX Simulation results for sealed type transformer

Fault	Duration (hours)
Oil leakage (without trip)	8
Oil leakage (not on-site repair)	159
Overloading	4
Insulation failure (bushings, without trip)	6
Insulation failure (not on-site repair)	258
Short-circuit (not on-site repair)	275

Table X Duration of the modified transitions of the second approach (sealed type transformer)

Transition	Description	Duration (hours)
t_1, t_9, t_{27}	Personnel is moving to transformer area	Exp(1)
t_{50}	Transformer arrives to repairing area	Exp(12)
t_{54}	Fault is repaired	Exp(180)
t_{60}	Transformer is transferred	Exp(2)

Table XI Simulation results for sealed type transformer (second approach)

Fault	Duration (hours)
Oil leakage (without trip)	8
Oil leakage (not on-site repair)	211
Overloading	4
Insulation failure (bushings, without trip)	6
Insulation failure (not on-site repair)	212
Short-circuit (not on-site repair)	205

include information such as type of transformer failure, duration of repair, position of transformer at the electric system, etc. One example of using these databases is to update the duration of stochastic transitions in the PN models.

Future research objectives include the modeling of other uncommon transformer faults and the more detailed analysis of the not on-site repair process. These would help in better understanding the diagnosis and repair and in acquiring better simulation results (by improving the accuracy of the stochastic transitions).

4. Conclusions

Transformer fault diagnosis and repair is a complex task that includes many possible types of faults and demands special trained personnel. This paper is concentrated on the investigation of the applicability of Stochastic Petri Nets in the modeling of transformer fault diagnosis and repair process. Simulation results for the most common types of transformer faults (overloading, oil leakage, short-circuit and insulation failure) are presented. The proposed methodology aims at identifying the transformer fault and estimating the duration for transformer repair.

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