Transformer Fault Diagnosis Modeling Using Petri Nets

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Abstract – **The reduction of the time needed for transformer fault diagnosis is an important task for transformer users. In this paper, Petri Nets are exploited, in order to simulate the transformer fault diagnosis process and to define the actions followed to repair the transformer.**

Keywords: Power System, Transformer, Transformer Fault Diagnosis, Transformer Repair, Artificial Intelligence, Petri Nets.

I. INTRODUCTION

The process of Electric Power System 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 components reliability. As the ultimate element in the electricity supply chain, the distribution 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 such 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].

In this paper, Petri Nets are proposed for modeling of transformer fault diagnosis process. 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]. The proposed method 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 paper is organized as follows: Section II describes the Petri Nets methodology. The application of Petri Nets to transformer fault diagnosis and the obtained results are described in Section III. Finally, Section IV concludes the paper.

II. OVERVIEW OF PETRI NETS

Petri Nets (PNs) were introduced in Carl A. Petri's 1962 Ph.D. dissertation [16]. Since that time, they have proved to be a valuable graphical and mathematical modeling tool applicable to many systems. As a graphical tool, PNs can be used as a visual communication aid similar to flow charts, block diagrams, and networks. As a mathematical tool, it is possible to set up state equations, algebraic equations, and other mathematical models governing the behavior of systems. For a formal introduction to PNs the reader is referred to [15, 17].

A PN is a particular kind of directed graph, together with an initial marking, M_0. The underlying graph of a PN is a directed, weighted, bipartite graph consisting of two kinds of nodes, called places and transitions, where arcs are either from a place to a transition or from a transition to a place. In graphical representation, places are drawn as circles, and transitions as either bars or boxes. If a marking (state) assigns to each place p a nonnegative integer k, it is called that p is marked with k tokens. Pictorially, k black dots (tokens) are placed in p.

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.

The presence of a token in a place is interpreted as holding the truth of the condition associated with the place. The only execution rule in a PN is the rule for transition enabling and firing. A transition t is considered as enabled if each input place p of t is marked with at least $w(p,t)$ tokens, where $w(p,t)$ is the weight of the arc from p to t. An enabled transition may or may not fire. A firing of an enabled transition t removes $w(p,t)$ tokens from all its input places p, and adds $w(p,t)$ tokens to each of its output places, where $w(t,p)$ is the weight of the arc from t to p. The movement of tokens through the PN graph represents the flow of information or control in the system [18-20].

Fig. 1 presents an example of a PN. The input place for transition t_0 is place p_0, and the set of output places for t_0 is $[p_1, p_2]$.

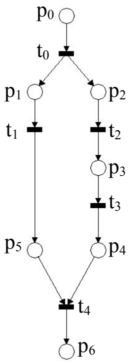

Fig. 1: Petri Net.

For problems that include the completion of an activity, it is necessary and useful to introduce time delays associated with transitions (activity executions) in their net models. Such a PN model is known as a deterministic timed net if the delays are deterministically given, or as a stochastic net, if the delays are probabilistically specified. In both cases, boxes of thick bars graphically represent transitions [17, 19].

The Stochastic Petri Net (SPN) model provides a more realistic representation of matter [21]. In SPNs transitions are associated with random variables that express the delay from enabling to the firing of the transition. The type of distribution in random variables can be uniform, exponential, etc.

Reachability is a useful concept of PNs. Each initial marking M_0 has a reachability set associated with it; this set consists of all the markings which can be reached from M_0 through the firing of one or more transitions.

Each marking, which can be reached from the initial marking, is referred to as a state. The reachability information is represented through a reachability graph, in which each node corresponds to a state, and the edges are associated with transitions. A directed edge is incident out of node M_i and into node M_{i+1} if and only if there exists a transition t_j whose firing changes the initial marking M_i to the marking M_{i+1}; the edge bears the label t_j. Reachability graphs enable as to find all the nodes which can be reached from M_i by the traversal of directed paths [22].

A PN is safe if the number of tokens in each place does not exceed 1 for any marking reachable from an initial marking M_0. A PN is live if, no matter what marking has been reached from M_0, it is possible to ultimately fire any transition of the net by progressing through some further firing sequence. A PN is reversible if, for each possible marking M, M_0 is reachable from M [17].

III. FAULT DIAGNOSIS USING PETRI NETS

This paper simulates the actions that are followed by the 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 tranformer fault diagnosis process.

To better model the transformer fault diagnosis process, stochastic PNs 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.

Fig. 2 presents the proposed PN model for transformer fault diagnosis, Fig. 3 shows the "not on-site repair" subnet (i.e. in case that the transformer repair is implemented in the factory), and Table 1 describes all places and transitions that constitute the PN models of Fig. 2 and 3. 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.

The proposed PN models the following transformer faults: overloading, short-circuit, insulation failure and oil leakage. The protection equipment that is used in a typical distribution transformer for fault detection 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.

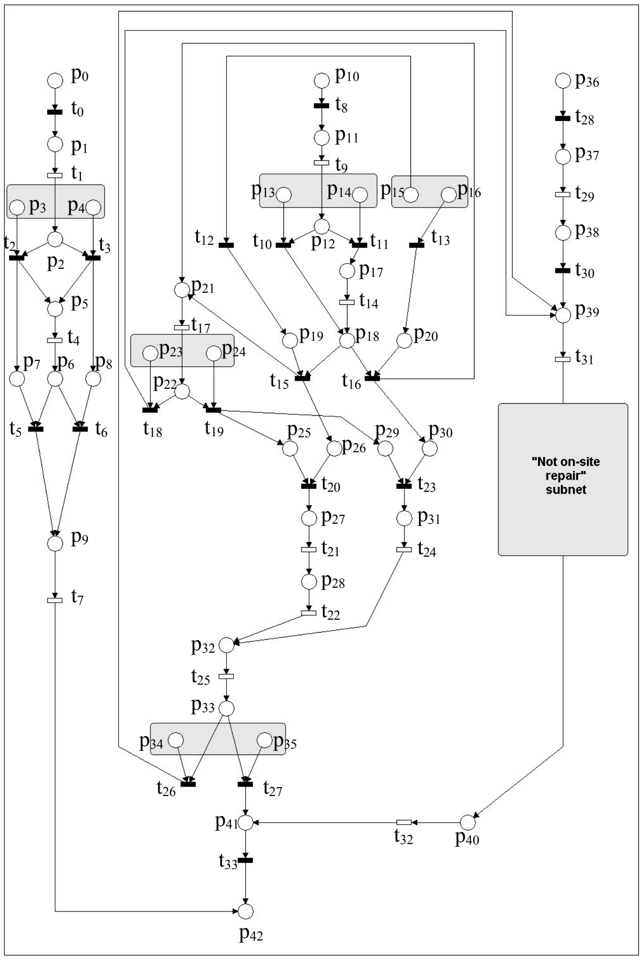

Fig. 2: PN model for transformer fault diagnosis.

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 restart 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 can not 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).

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. They also check for the kind of damage. There are two possible contingencies: either the level of the oil indicator is low ($\boldsymbol{p_{15}}$), or there are air bubbles behind the glass of the Buchholz relay ($\boldsymbol{p_{16}}$). 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 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 ($\boldsymbol{p_{25}}$ and $\boldsymbol{p_{29}}$) and the specific type ($\boldsymbol{p_{26}}$ or $\boldsymbol{p_{30}}$) enables the transition $\boldsymbol{t_{20}}$ or $\boldsymbol{t_{23}}$. 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 Fig. 3 is then models the transformer fault diagnosis and repair process.

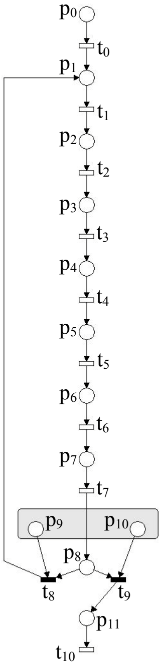

Fig. 3: PN model for the "not on-site repair" subnet

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 Fig. 2), otherwise the repairing procedure is repeated.

Considering the sequence of transition firings and all marking reachable from the initial marking, the reachability graph of the Petri subnet of Fig. 3 is drawn in Fig. 4 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, it is validated that the constructed model is safe, live and reversible. The verification of these important PN properties assures that our subnet is feasible and deadlock-free [18].

	Main Petri net	p_{28}:	Lost oil needs to be replaced
p_0:	Oil thermometer alarms	t_{22}:	Lost oil is replaced
t_0:	Alarm is activated	p_{29}:	Possibility for repairing insulation failure
p_1:	Personnel is notified	p_{30}:	Problem of insulation failure
t_1:	Personnel is moving to transformer area	t_{23}:	Repair of insulation failure is possible
p_2:	Existence of alarm or trip?	p_{31}:	Need to replace problematic external parts
p_3:	Oil thermometer still alarms	t_{24}:	Parts are replaced
t_2:	Alarm is still activated	p_{32}:	Check if everything works properly
p_4:	Oil thermometer tripped	t_{25}:	Transformer is checked
t_3:	Trip is activated	p_{33}:	Is transformer working properly?
p_5:	Need to check the loads	p_{34}:	It is not working properly
t_4:	Loads are checked	t_{26}:	Fault still exists
p_6:	Does transformer need to restart?	p_{35}:	It is working properly
p_7:	It doesn't need to restart	t_{27}:	Fault is repaired
t_5:	No restart is needed	p_{36}:	Buchholz relay trips
p_8:	It needs to restart	t_{28}:	Trip is activated
t_6:	Transformer is restarting	p_{37}:	Personnel is notified
p_9:	Loads have to be reduced properly	t_{29}:	Personnel is moving to transformer area
t_7:	Loads are reduced properly	p_{38}:	Identification of transformer’s fault
p_{10}:	Buchholz relay alarms	t_{30}:	Existence of a powerful short-circuit
t_8:	Alarm is activated	p_{39}:	Transformer needs to disconnect
p_{11}:	Personnel is notified	t_{31}:	Transformer is disconnected
t_9:	Personnel is moving to transformer area	p_{40}:	Transformer arrives in area of installation
p_{12}:	Existence of alarm or trip?	t_{32}:	Transformer is reinstalled
p_{13}:	Buchholz relay tripped	p_{41}:	Transformer is ready to work
t_{10}:	Trip is activated	t_{33}:	Transformer is restarted
p_{14}:	Buchholz relay still alarms	p_{42}:	Transformer reworks properly
t_{11}:	Alarm is still activated		**"Not on-site repair" subnet**
p_{15}:	Low level of oil indicator	p_0:	Transformer is sending to repairing area
t_{12}:	Oil volume has reduced	t_0:	Transformer arrives to repairing area
p_{16}:	Air bubbles in Buchholz relay's glass	p_1:	Oil has to be removed
t_{13}:	Air bubbles are observed	t_1:	Oil is removed
p_{17}:	Transformer needs to stop	p_2:	Inside search is needed
t_{14}:	Transformer is stopped	t_2:	Tank is opened
p_{18}:	Existence of oil leakage or insulation failure?	p_3:	Check for the exact type of fault
p_{19}:	Oil leakage	t_3:	Check is done
t_{15}:	Existence of oil leakage	p_4:	Identification of fault
p_{20}:	Insulation failure	t_4:	Fault is repaired
t_{16}:	Existence of insulation failure	p_5:	Transformer has to be reassembled
p_{21}:	Check for the exact type of fault	t_5:	Transformer is reassembled
t_{17}:	Transformer is checked	p_6:	Oil has to be added
p_{22}:	Is it possible repair fault on the spot?	t_6:	Oil is added
p_{23}:	It is not possible to repair	p_7:	Check for the proper operation
t_{18}:	Fault cannot be repaired on the spot	t_7:	Check is done
p_{24}:	It is possible to repair	p_8:	Is transformer working properly?
t_{19}:	Fault can be repaired on the spot	p_9:	It is not working properly
p_{25}:	Possibility for repairing oil leakage	t_8:	Fault still exists
p_{26}:	Problem of oil leakage	p_{10}:	It is working properly
t_{20}:	Repair of oil leakage is possible	t_9:	Fault is repaired
p_{27}:	Personnel prepares to repair transformer	p_{11}:	Transformer is ready to be sent back in its area
t_{21}:	Transformer is repaired	t_{10}:	Transformer is transferred

Table 1: Description of PN places and transitions

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]). In Table 2, simulation results for fault diagnosis and repair are presented.

Fault	Duration
Oil leakage (without trip)	8 hours
Oil leakage (not on-site repair)	8 days
Overloading	5 hours
Insulation failure (bushings, without trip)	6 hours
Insulation failure (not on-site repair)	8 days
Short-circuit	8 days

Table 2: Simulation results

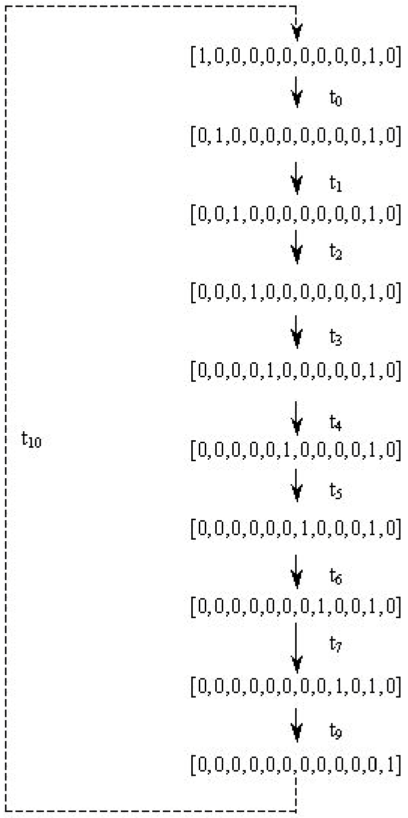

Fig. 4: Reachability graph of the PN model of Fig. 3

IV. 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.

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

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