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Research Article

Fuzzy Timing Petri Net for Fault Diagnosis in Power System

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A model-based system for fault diagnosis in power system is presented in this paper. It is based on fuzzy timing Petri net (FTPN). The ordinary Petri net (PN) tool is used to model the protective components, relays, and circuit breakers. In addition, fuzzy timing is associated with places (token)/transition to handle the uncertain information of relays and circuits breakers. The received delay time information of relays and breakers is mapped to fuzzy timestamps, π (τ), as initial marking of the backward FTPN. The diagnosis process starts by marking the backward sub-FTPNs. The final marking is found by going through the firing sequence, σ, of each sub-FTPN and updating fuzzy timestamp in each state of σ. The final marking indicates the estimated fault section. This information is then in turn used in forward FTPN to evaluate the fault hypothesis. The FTPN will increase the speed of the inference engine because of the ability of Petri net to describe parallel processing, and the use of time-tag data will cause the inference procedure to be more accurate.

1. Introduction

A rapid and correct fault diagnosis is crucial for power system restoration. However, as the complexity of power system increases, fault diagnosis, especially in complicated faults or incorrect operation of protective devices, becomes a very difficult task in the limited short time. This situation has made it necessary to develop intelligent systems to support operators in their decision making process. Over the last two decades different artificial intelligent (AI) approaches have been proposed for fault diagnosis in power system. Most attempts to date have relied on the use of expert system [1] or neural network [2] technology. Expert-system-based approaches have been the most successful so far, while neural-network-based methods continue to improve their performance. Previous reported expert systems for fault diagnosis use either rule-based or model-based approach [3]. The first approach may work well only in simple fault cases. However, to diagnose a fault in complicated cases, it needs a huge number of rules to describe the complicated protection system behavior. As a result, the acquisition and maintenance of such a system is tedious and difficult [3].

On the other hand, model-based diagnostic (MBD) methods are suitable to network fault diagnosis because the power systems and protective relays can be modeled as discrete event systems. MBD covers a wide range of fault scenarios than heuristic reasoning because it is based on the system behavioral analysis. It can detect malfunctioning equipment in the early stages [4]. Nevertheless, the model-based system requires more inference time. As a result, there is a need to enhance speed and performance of diagnoses system. Parallel inference processing and time sequence information of protective relays and circuit breakers is important factor for reducing fault diagnosis processing time [3]. This is so because parallel processing increases the inference procedure and real-time availability of the relay information allows expert systems to reduce the number of hypotheses [4].

One of the powerful tools for modeling parallel processing is Petri net [5]. There have been some proposed model-based systems using Petri net and colored and timed Petri net for faster inference [6, 7]. In [6] final marking of forward and backward Petri nets model is compared to make a decision for faulted section area. However, timestamp of protective devices has not been considered on that model and the model which is proposed in [7] cannot handle the uncertain and missing data. There have also been works on expert systems that use time-tag information of actuated relays and tripped circuit breakers through sequence event recorder (SER) in fault diagnosis [8].

This paper proposes fuzzy timing Petri net to handle uncertain information of protective device and to overcome the drawbacks of previous works. Petri nets have also been successfully applied in power system for verification of concurrent switching sequences [9] and modeling of transmission line protection relaying scheme [10].

The paper is organized as follows. In the next section Petri net will be introduced. A brief and concise description of the fuzzy timing petri net (FTPN) will be given in Section 3. Diagnosis process is described in Section 4. In Section 5, the proposed FTPN is used for diagnosing fault in a simple and typical line. The application will be presented in Section 7. The final section is conclusion.

2. Petri Nets

Petri nets (PNs), as a graphical and mathematical tool, provide a uniform environment for modeling and design of discrete event systems. It is a particular kind of bipartite directed graphs populated by three objects. These objects are places, transitions, and directed arcs connecting places to transitions and transitions to places. Pictorially, places are depicted by circles and transitions by bars [5].

The ordinary Petri nets do not include any concept of time explicitly. With this class of nets, it is only possible to describe the logical structure of the modeled system, but not its time evolution. Responding to the need for the temporal performance of discrete-event systems and modeling concurrent systems with time constraints, various timed extensions of Petri nets have been proposed by attaching timing constraints to transitions, places, and/or arcs [5].

Later, other researchers introduced fuzzy Petri net for knowledge representation to deal with fuzzy production rules [11] and fuzzy timing Petri net (FTPN) for performance, evaluation, and specification of dynamic concurrent system [12, 13] under uncertainty and imprecision.

3. Fuzzy Timing Petri Net and Extended Fuzzy Timing Petri Net

Fuzzy-timing Petri net (FTPN) has been proposed by Zhou and Murata [12] and is defined as follows.

The static structure of FTPN is a five-tuple structure, $N = (P, T, A, D, \mathrm{FT})$ where $P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places, $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions, $A \subseteq (P \times T) \cup (T \times P)$ is a set of arcs (flow relation), D is a set of all fuzzy delays $d_{tp}(\tau)$ associated with arcs $\subseteq (T \times P)$, and FT is a set of all fuzzy timestamp, where a fuzzy timestamps, $\pi(\tau) \in$ FT is associated with each token and each place. It is a fuzzy time function or possibility distribution giving the numerical estimate of the possibility that a particular token arrives at time τ in a particular place.

The extended fuzzy-timing Petri net (EFTPN) model is a FTPN with the default value of $d_{tp}(\tau)$ being $(0,0,0,0)$ and with additional function $\mathrm{CT} : T \to Q^+ \times Q^+ \times (Q^+ \cup \infty)$, which is a mapping from transition T to firing intervals with possibility p, that is, each transition is associated with a firing interval, $p[a, b]$, $(a \le b)$, where the default interval is $1[0,0]$ (a transition definitely fires as soon as it is enabled) (possibility $p \in [0,1]$). P is 1 if transition t is not in conflict with any other transition. When different chances are to be assigned to transitions in structural conflict, P can be less than 1. Q^+ is set of positive rational numbers.

The dynamic evolution of marking in an FTPN is the same as that of an ordinary PN except that fuzzy timestamps $\pi(\tau)$, fuzzy enabling times $e(\tau)$, and fuzzy occurrence time $o(\tau)$ need to be computed and updated each time when a transition firing (atomic action) occurs. Fuzzy enabling time $e_t(\tau)$ of transition t is the possibility distribution of latest arrival time among the arrival times of all tokens in input places of t that are necessary to enable the transition t in the untimed case and is given by

$$e_t(\tau) = \mathrm{latest}\{\pi_i(\tau),\ i = 1, 2, \ldots, n\}. \tag{3.1}$$

Fuzzy occurrence time $O_t(\tau)$ of transition t is the possibility distribution of the time at which the transition t starts firing and is given by

$$O_t(\tau) = \min\{e_t(\tau), \mathrm{earliest}\{e_i(\tau),\ i = 1, 2, \ldots m\}\}. \tag{3.2}$$

The fuzzy timestamp $\pi_{tp}(\tau)$, the possibility distribution of the time at which a token arrives in an output place of t, is given by the extended addition of $O_t(\tau)$ and $d_{tp}(\tau)$ or

$$\pi_{tp}(\tau) = O_t(\tau) \oplus d_{tp}(\tau). \tag{3.3}$$

Here $\pi_{tp}(\tau)$ is updated fuzzy timestamps in an FTPN. When there are m transitions in conflict enabled with their fuzzy enabling times, $e_i(\tau)$, $i = 1, 2, \ldots .m$, and $\mathrm{CT}(t_i) = p_i[a_i, b_i]$, then fuzzy occurrence time $O_t(\tau)$ of transition t is computed as follows:

$$O_t(\tau) = \min\{e_t(\tau) \oplus p_t(a_t, a_t, b_t, b_t), \mathrm{earliest}\{e_i(\tau) \oplus p_i(a_i, a_i, b_i, b_i), i = 1, 2, m\}\}. \tag{3.4}$$

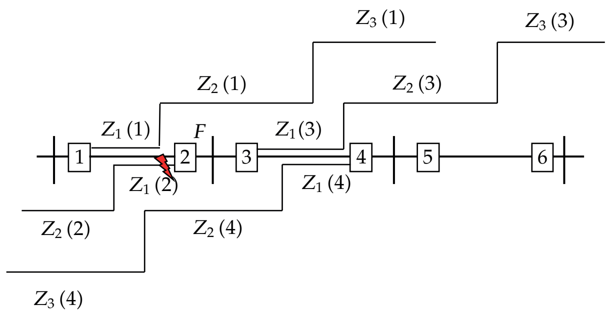

Figure 1: A simple and typical transmission line.

4. Diagnosis Process

In the following discussion it is assumed that the protective devices have arrived in their final status. The general philosophy of diagnosis task is based on model-based reasoning: the comparison between the observed and predicted behaviors of the system [14–16]. Diagnosis is performed in two-step reasoning process. The first step is based on forward reasoning (data driven). Having the final status of protective devices, the initial marking of the backward FTPN is performed by assigning fuzzy time function $\pi(\tau)$ to relevant places. That is to say, timestamps information of relays and breakers is used as the initial fuzzy timestamps $\pi_0(\tau)$. In other words, $\pi_0(\tau)$ is the numerical estimate of possibility that a particular protective device has been operated. Processing the FTPN as a forward reasoning to get final marking would get the fault hypotheses. Indeed in the first step of diagnosis, both the candidates of faulted section and estimated time that fault has been cleared by protective devices are derived.

Fault simulation process takes place in the second step of diagnosis task and is based on backward reasoning (goal driven). The predicate behavior of protective devices, in the case of occurring fault, is modeled by the forward FTPN. The fuzzy timestamp of token arriving at the final place of backward FTPN is compared with fuzzy timestamp of token in the final state of forward FTPN.

A default threshold value, λ, is used to validate the discrepancy of two fuzzy timestamps. If discrepancy of two fuzzy timestamps is larger than threshold value, then the fault candidate is assumed to be correct. Otherwise the simulation process is repeated again by executing the forward FTPN by assuming the malfunction of appropriate relay. For instance, by exchanging the possibility of transition t_2 and t_3 in Figure 2 the malfunction of relay R_1 is simulated.

5. Example

For illustration purposes, consider a simple and typical transmission line depicted in Figure 1. Suppose a fault has occurred on point F. Furthermore, assume that signals have been received and recorded with precise time tags or in a chronological order and available through SER.

The forward and backward FTPN models with main protection (CB_2) and primary backup protection (CB_1, CB_4) for this point are shown in Figure 2 and Figure 4, respectively.

In Figure 2, the token in place P_1 shows absence of the fault, F, and P_5, P_9, and P_{13} represent readiness of the relays R_2, R_1, and R_4, respectively, Places P_{16}, P_{17}, and P_{18}

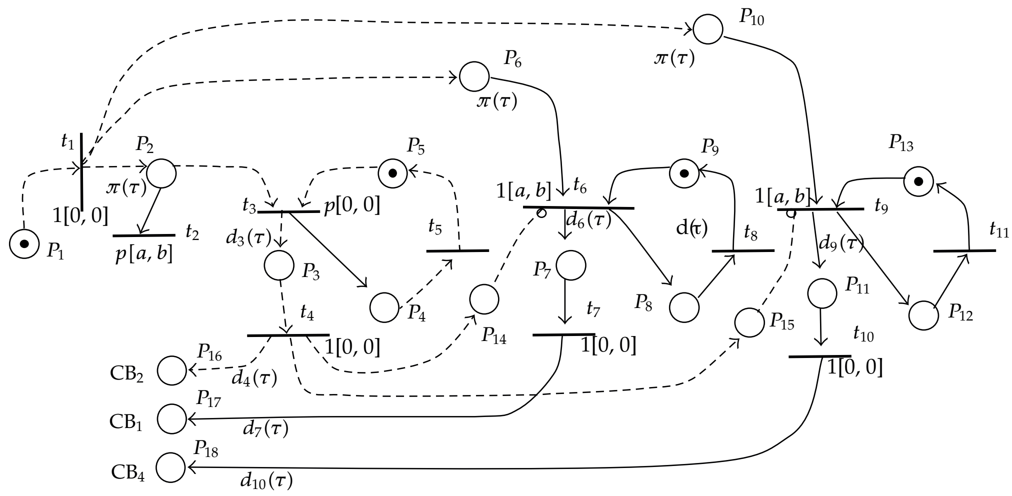

Figure 2: Forward FTPN model for fault at F point in Figure 1. σ_1: $M_0[t_1\rangle\ M_1[t_3\rangle\ M_2[t_4\rangle\ M_3[t_5\rangle\ M_4$, σ_2 : $M_0[t_1\rangle\ M_5[t_2\rangle\ M_6[t_6 t_9\rangle\ M_7[t_7\ t_{10}\rangle\ M_8[t_8\ t_{11}\rangle\ M_9$, $M_0 = (P_1\ P_5\ P_9\ P_{13})$, $M_1 = M_5\ (P_2\ P_5\ P_6\ P_9\ P_{10}\ P_{13})$, $M_2 = (P_3\ P_4\ P_6\ P_9\ P_{10}\ P_{13})$, $M_3 = (P_4\ P_6\ P_9\ P_{10}\ P_{13}\ P_{14}\ P_{15}\ P_{16})$, $M_4 = (P_5\ P_6\ P_9\ P_{10}\ P_{13}\ P_{14}\ P_{15}\ P_{16})$, $M_6 = (P_5\ P_6\ P_9\ P_{10}\ P_{13})$, $M_7 = (P_5\ P_7\ P_8\ P_{11}\ P_{12})$, $M_8 = (P_5\ P_8\ P_{12}\ P_{17}\ P_{18})$, $M_9 = (P_5\ P_9\ P_{13}\ P_{17}\ P_{18})$, $P_5 = R_2$, $P_9 = R_1$, $P_{13} = R_4$, $P_{16} = \text{CB}_2$, $P_{17} = \text{CB}_1$, $P_{18} = \text{CB}_4$. σ_1 and σ_2 are the firing sequences, in the case of correct actuated and nonactuated of relay R_2, respectively, M_0 to M_9 are marking states of the FPTN.

correspond to circuit breakers CB_2, CB_1, and CB_4, respectively, The occurrence of F is represented by the transition t_1, which deposits a token in places P_2, P_6, and P_{10} to indicate that the fault is present.

In this case, transitions t_3, t_6, and t_9 are enabled and can fire within their interval time. This corresponds to sensing the fault by relay R_2, R_1, and R_4. However, transitions t_7 and t_{10} will be fired after transition t_3 because their firing interval is later than t_3. The static default of firing interval of transition t_3 is $[0, 0]$. Firing transitions t_3, t_6, and t_9 correspond to sending trip signals and transitions t_4, t_7, and t_{10} correspond to opening the circuit breakers CB_2, CB_1, and CB_4, respectively.

A fuzzy delay $d_{tp}(\tau)$ is associated with arcs (t, p) from transitions t_4, t_7, and t_{10} to places P_{16}, P_{17}, and P_{18}, respectively, to map the operating time of CB*s*. The $d_{tp}(\tau)$ of other arcs are set to $(0, 0, 0, 0)$, which means that transitions connected to these arcs fire and the token will be available to their corresponding output place immediately. The sink transitions t_2 is fired in the case of malfunction of relay R_2. Since backup relays send trip signal after main relays, the firing transitions of the FTPN corresponding to these relays should be in correct sequence.

To do this, a static time interval $1[a, b]$ $(a \leq b)$ is assigned to the transitions t_6 and t_9 to ensure that these transitions will be fired after transitions t_3 and t_4. Moreover, in the case of malfunction of CB_2, places P_{14} and P_{15} will not get tokens. Therefore, transitions t_6 and t_9 can fire within their firing intervals. The firing sequences and its marking of the forward FTPN are shown in the bottom of Figure 2.

The backward FTPN consists of three sub-FTPN modules (see Figure 4). Each of the sub-FTPNs corresponds to one CB and its corresponding relay protection module. There are three kinds of places in this FTPN: those which get marking in the case of receiving signals (shown with a circle), the second type that get token in the case of nonreceiving signals from

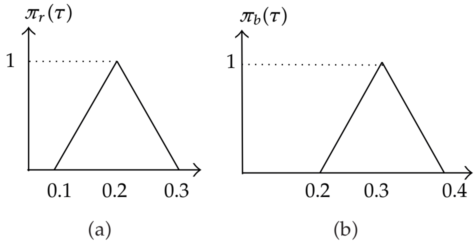

Figure 3: Two typical fuzzy time functions (a) for delay time of relay R_2 and (b) for delay time of breaker CB_2.

CBs and relays (shown with two circles), and the third one which are used as auxiliary places (shown also with a circle).

In Figure 2, places P_1, P_4, P_9, P_{12}, P_{17}, and P_{20} correspond to CB_1, R_1, CB_2, R_2, CB_4, and R_4, respectively. In the case of non-receiving signal from relay or CB, the places indicated by two circles get tokens.

As previously mentioned, suppose a fault has occurred at point F and information received from relays and breakers with their time delay is R_2 $(0.2\,s)$ and CB_2 $(0.3\,s)$. Diagnosing process starts by marking appropriate places of the backward sub-FTPN (Figure 4) and assigning each token with fuzzy time function. The goal is to find the fuzzy time function of final state of the backward FTPN in its firing sequences.

To do this, first fuzzy enabling time of transition t_{11} is calculated by (3.1). Then the fuzzy occurrence time of t_{11} is found by (3.2). The next step is to compute fuzzy timestamp of place P_{11}. It is calculated by (3.3). The same procedure is done for the next transitions/places in the firing sequences σ_1 (shown at the bottom of Figure 4(a)) to reach the place F.

At this stage of diagnosis, the fuzzy timestamps at the place F are compared with the simulation, result of Figure 2. If discrepancy of two fuzzy timestamps is larger than threshold value and receiving data is compatible with simulation, then the fault candidate is assumed to be correct. Otherwise the simulation process is repeated. In the second round of execution of forward FTPN, transition t_2 is first fired to simulate the malfunction of relay R_2 and the result is compared to backward FTPN. The marking of the backward sub-FTPN2 can be shown by vector $M = (P_9\ P_{10}\ P_{11}\ P_{12}\ P_{13}\ P_{14}\ P_{15}\ P_{16}\ P_{25})$, the last place is the fault section estimation and designated by F in place P_{25}. Therefore, with receiving information from R_2 and CB_2, the initial marking is $M_0 = (1\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0)^T$, number 1 indicates that places P_9 and P_{12} both get token and zero means otherwise. With this marking only transition t_{11} is enabled and can fire. Transition t_{12} is not enabled because the place with inhibitory arc connected to it is marked. Firing transition t_{11} removes token from places P_9 and P_{12} and deposites one token in the places P_{11} and P_{12}. After firing this transition the new marking is $M_1 = (0\ 0\ 1\ 1\ 0\ 0\ 0\ 0)^T$. Having token in places P_{11} and P_{12} the transition t_{14} is now enabled and can fire. Firing t_{14} makes the new marking state as $M_2 = (0\ 0\ 0\ 1\ 0\ 0\ 1\ 0)^T$. The final marking of this sub-FTPN will be $M_4 = (0\ 0\ 0\ 1\ 0\ 0\ 0\ 1)^T$. The broken line in Figure 6 shows the traverse of token in sub-FTPN2. Having delay time of R_2 and CB_2, the initial fuzzy timestamps would be as in Figure 3.

With these fuzzy timestamps at the places P_9 and P_{12}, first fuzzy enabling time of transition t_{11} should be found.

$e_{11}\ (\tau) = \text{latest}\ \{\pi_r\ (\tau), \pi_b\ (\tau)\ \} = \text{latest}\ \{(0.1, 0.2, 0.2, 0.3),\ (0.2, 0.3, 0.3, 0.4)\} = (0.2, 0.3, 0.3, 0.4)$. Then, fuzzy occurrence time of t_{11} is computed (see (3.2)): $o_{11}(\tau) =$

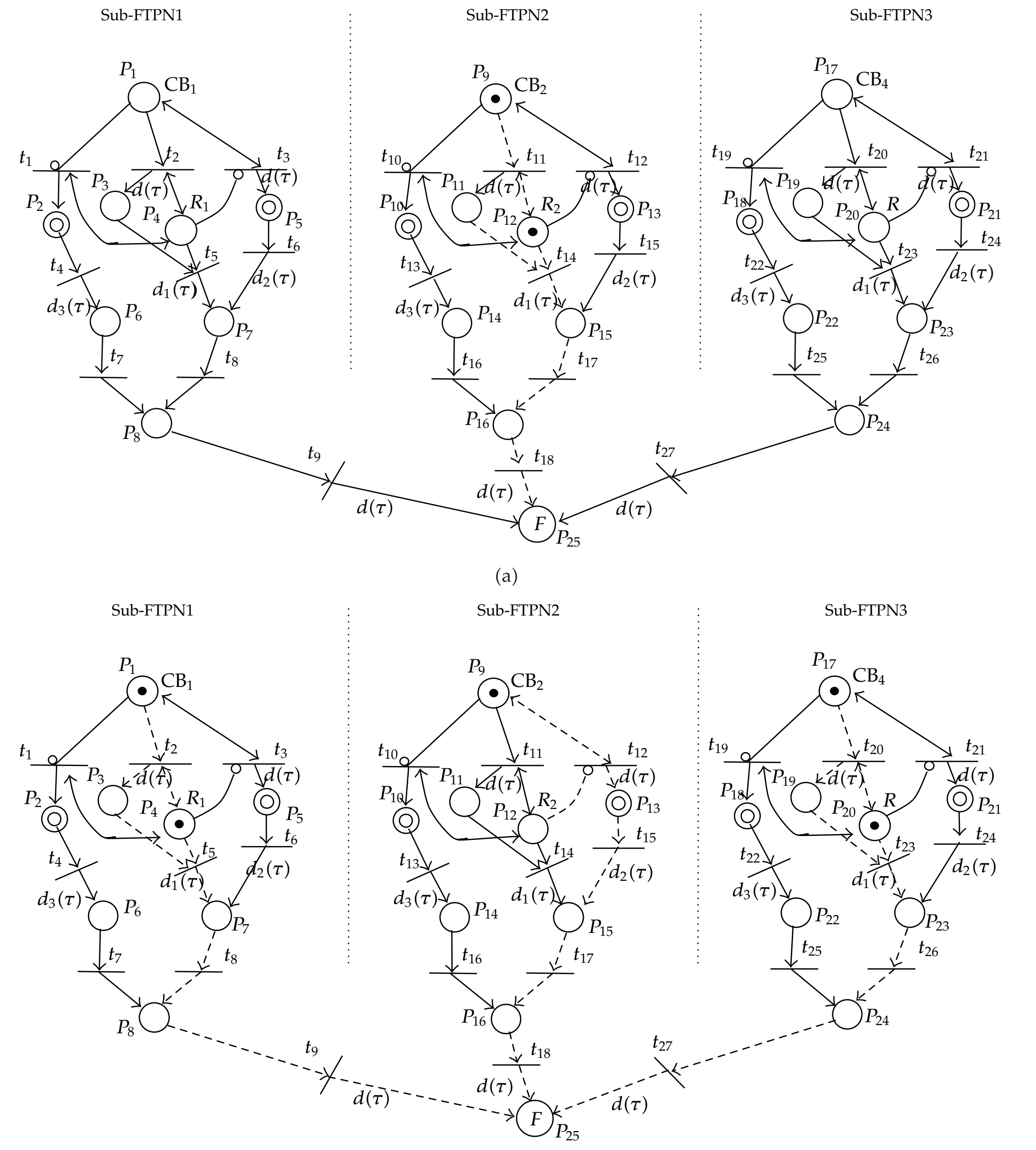

Figure 4: The backward FTPN model of Figure 1 for fault at point F (shown by place P_{25}). CB_2 and R_2 correspond to the main protection, and CB_1, R_1, CB_4, and R_4 correspond to the backup protection. (a) Information received from R_2 and CB_2. σ_1 is the firing sequence of sub-FTPN2. $\sigma_1 = M_0[t_{11}\rangle\, M_1[t_{14}\rangle\, M_2[t_{17}\rangle\, M_3[t_{18}\rangle\, M_4$, $M_0 = (P_9\ P_{12})$, $M_1 = (P_{11}\ P_{12})$, $M_2 = (P_{12}\ P_{15})$, $M_3 = (P_{12}\ P_{16})$, $M_4 = (P_{12}\ P_{25})$. (b) Information received from CB_2, CB_1, R_1, CB_4, and R_4. σ_1, σ_2, and σ_3 are firing sequence of sub-FTPN1, sub-FTPN2, and sub-FTPN3, respectively, $\sigma_1 = M_0[t_2\rangle\, M_1[t_5\rangle\, M_2[t_8\rangle\, M_3[t_9\rangle\, M_4$, $\sigma_2 = M_5[t_{12}\rangle\, M_6[t_{15}\rangle\, M_7[t_{17}\rangle\, M_8[t_{18}\rangle\, M_9$, $\sigma_3 = M_{10}[t_{20}\rangle\, M_{11}[t_{23}\rangle\, M_{12}[t_{26}\rangle\, M_{13}[t_{27}\rangle\, M_{14}$, $M_0 = (P_1\ P_4)$, $M_1 = (P_3\ P_4)$, $M_2 = (P_4\ P_7)$, $M_3 = (P_4\ P_8)$, $M_4 = (P_4\ P_{25})$, $M_5 = (P_9)$, $M_6 = (P_9\ P_{13})$, $M_7 = (P_9\ P_{15})$, $M_8 = (P_9\ P_{16})$, $M_9 = (P_9\ P_{25})$, $M_{10} = (P_{17}\ P_{20})$, $M_{11} = (P_{19}\ P_{20})$, $M_{12} = (P_{20}\ P_{23})$, $M_{13} = (P_{20}\ P_{24})$, $M_{14} = (P_{20}\ P_{25})$.

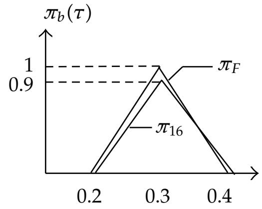

Figure 5: Comparison of two possibility distributions π_F and π_{16}.

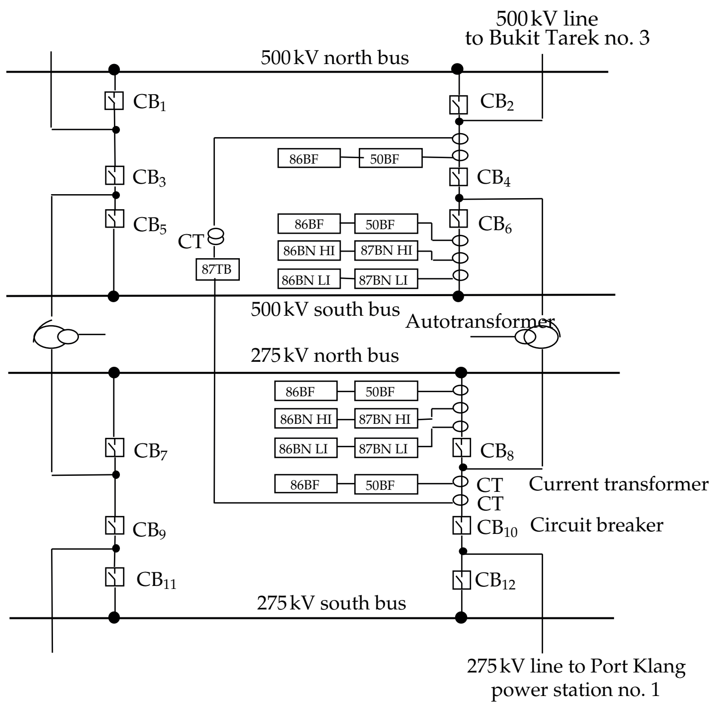

Figure 6: A simplified protection scheme of Kapar substation.

min $\{(0.2, 0.3, 0.3, 0.4), \text{earliest } \{(0.2, 0.3, 0.3, 0.4)\}\} = (0.2, 0.3, 0.3, 0.4)$. Next fuzzy timestamp of place P_{11} is calculated (3.3) as $\pi_{11}(\tau) = o_{11}(\tau) \oplus d_{11}(\tau) = (0.2, 0.3, 0.3, 0.4) \oplus (0, 0, 0, 0) = (0.2, 0.3, 0.3, 0.4)$. Here it is assumed that the fuzzy delay time $d_{11}(\tau)$ is $(0, 0, 0, 0)$.

This process is performed for firing sequence σ_1 until the final state of sub-FTPN2 (i.e., place $P_{25}(F)$). In this case, the fuzzy time function of place F will be $\pi_F(\tau) = (0.2, 0.3, 0.3, 0.4)$.

Having fuzzy timestamps of fault hypothesis in the backward FTPN, the fuzzy timestamps of final marking in the forward FTPN (see Figure 2) are to be computed. The following are assumed:

> $\pi_1(\tau) = (0, 0, 0, 0)$, means that token in place P_1 is immediately available. $\pi_5(\tau) = (0.1, 0.2, 0.2, 0.3)$ and $\pi_9(\tau) = \pi_{11}(\tau) = (0.3, 0.4, 0.4, 0.5)$.

Having token in place P_2, the fuzzy enabling time of transition t_3 is

$$e_3(\tau) = \text{latest}\{\pi_0(\tau), \pi_5(\tau)\} = (0.1, 0.2, 0.2, 0.3). \tag{5.1}$$

To compute fuzzy occurrence time of transition t_3, the earliest enabling time of t_2 and t_3 is found first as follows.

earliest$\{e_3(\tau)\oplus 0.9(0.01, 0.01, 0.03, 0.03), e_2(\tau)\oplus 0.1(0.25, 0.25, 0.4, 0.4)\}$ = earliest$\{0.1, 0.2, 0.2, 0.3) \oplus 0.9(0.01, 0.01, 0.03, 0.03), (0, 0, 0, 0) \oplus 0.1(0.25, 0.25, 0.4, 0.4)\}$ = $\max(0.9, 0.1)$, $\min(0.11, 0.25), \min(0.21, 0.25)$, $\min(0.21, 0.4), \min(0.31, 0.4)\}$ = $0.9(0.11, 0.21, 0.21, 0.31)$.

Therefore, the fuzzy occurrence of t_3 is computed as follows:

$o_3(\tau) = \min\{e_3(\tau)\oplus 0.9(0.01, 0.01, 0.03, 0.03)$, earliest$\{e_3(\tau) \oplus 0.9(0.01, 0.01, 0.03, 0.03), e_2(\tau) \oplus 0.1(0.25, 0.25, 0.4, 0.4\}\} = \min\{(0.1, 0.2, 0.2, 0.3) \oplus 0.9(0.01, 0.01, 0.03, 0.03)$, earliest$\{e_3(\tau) \oplus 0.9(0.01, 0.01, 0.03, 0.03), e_2(\tau) \oplus 0.1(0.25, 0.25, 0.4, 0.4\}\} = \min\{0.9(0.11, 0.21, 0.21, 0.31), 0.9(0.11, 0.21, 0.21, 0.31)\} = 0.9(0.11, 0.21, 0.21, 0.31)$.

Now fuzzy timestamp of place P_3 is found as follows:

$\pi_3(\tau) = o_3(\tau) \oplus d_3(\tau)$, where $d_3(\tau)$ is fuzzy delay time from transition t_3 to place P_3.

$\pi_3(\tau) = 0.9(0.11, 0.21, 0.21, 0.31) \oplus (0, 0, 0, 0) = 0.9(0.11, 0.21, 0.21, 0.31)$. Then the fuzzy occurrence transition t_4 would be as follows:

$$\begin{aligned} o_4(\tau) &= e_4(\tau) = \pi_3(\tau) = 0.9(0.11, 0.21, 0.21, 0.31), \\ \pi_{16}(\tau) &= o_4(\tau) \oplus d_4(\tau) = 0.9(0.11, 0.21, 0.21, 0.31) \oplus (0.1, 0.1, 0.1, 0.1) \\ &= 0.9(0.21, 0.31, 0, 31, 0, 41). \end{aligned} \tag{5.2}$$

6. Comparison of Two Fuzzy Timestamps

At this stage of diagnosis the comparison of two fuzzy timestamps π_F and π_{16} derived from forward and backward FTPN is to be evaluated. Refer to [13]. The possibility of $\pi_F = \pi_{16}$ may be found as follows (see Figure 5):

$$\prod(\pi_F = \pi_{16}) = \min\left\{\prod(\pi_F \leq \pi_{16}) \prod(\pi_{16} \leq \pi_F)\right\} = \min(0.9, 1) = 0.9. \tag{6.1}$$

If the threshold value, λ, is assumed to be $\lambda = 0.8$, therefore it is concluded that a fault has occurred at point F and relay R_2 and breaker CB_2 have operated correctly.

7. Application

Figure 6 depicts one of the existing Malaysian substations, the so-called Kapar substation. It consists of two breaker and half systems (500 kV and 275 kV), which are connected by autotransformer. Since the complete protection scheme of the substation is complex, only simplified protection version will be used for one of the buses, say 275 kV north bus.

At the 275 kV north bus—at the CB_8 side—the following protective devices are used:

87BN HI: high impedance busbar relay (trips 86N HI),

87BN LI: low impedance busbar relay (trips 86N LI),

50BF: breaker failure (trips 86BF),

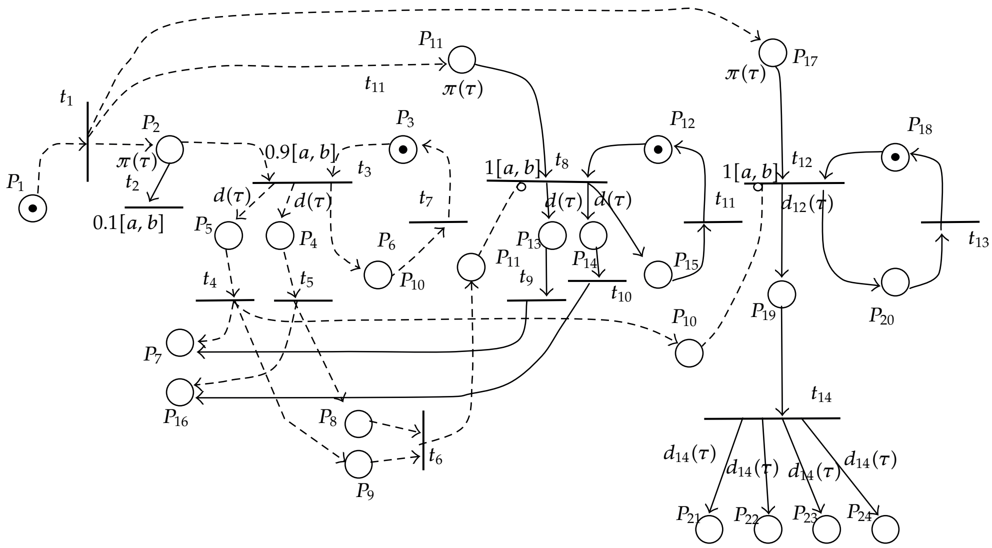

Figure 7: The forward FTPN model of protection scheme for fault at 275 kV north bus bar of Kapar substation. The marking state of FTPN before occurrence of fault. The token in P_1 shows absence of fault, and firing transition t_1 indicates the occurrence of fault. Tokens in places P_3, P_{12}, and P_{18} indicate the readiness of main, local backup, and breaker failure relays, respectively. The broken lines show the FTPN route in its firing sequences (in the case of correct operation of main relay and circuit break).

86BF: breaker failure lockout relay,

86BN HI: high impedance busbar lockout relay,

86BN LI: low impedance busbar lockout relay.

The same protection scheme is at the 500 kV south bus. In addition, the autotransformer is protected by relay 87TB, which is a biased transformer differential relay.

Suppose a fault occurs at 275 kV north bus of the Kapar substation. If the main relay (the busbar differential protection-87BN-HI) senses the fault and operates correctly, it then sends trip to CB_8 and CB_7 to isolate the busbar from fault. This scenario is modeled by the forward and backward FTPN and shown in Figures 7 and 8, respectively. If the main relay fails to operate, the local backup relay (87BN-LI) sends trip signal to the breakers CB_8 and CB_7. In the case of malfunction of circuit breaker CB_8 the breaker failure relay will send trip signal to the circuit breakers CB_7, CB_4, CB_6, and CB_{10}. The broken lines in the forward FTPN models (Figure 7) show the route of FTPN in their firing sequences corresponding to their protection scheme.

In the backward FTPN models the token in place F shows the estimated fault section, which in this case is 275 kV busbar. This estimated fault section hypothesis in turn is compared with its relevant forward FTPN models. The procedure is similar as the one explained in Section 6.

8. Conclusions

A new model-based reasoning for power system fault diagnosis is proposed in this paper. It is based on fuzzy timing Petri net. It is believed that this proposed system could cover

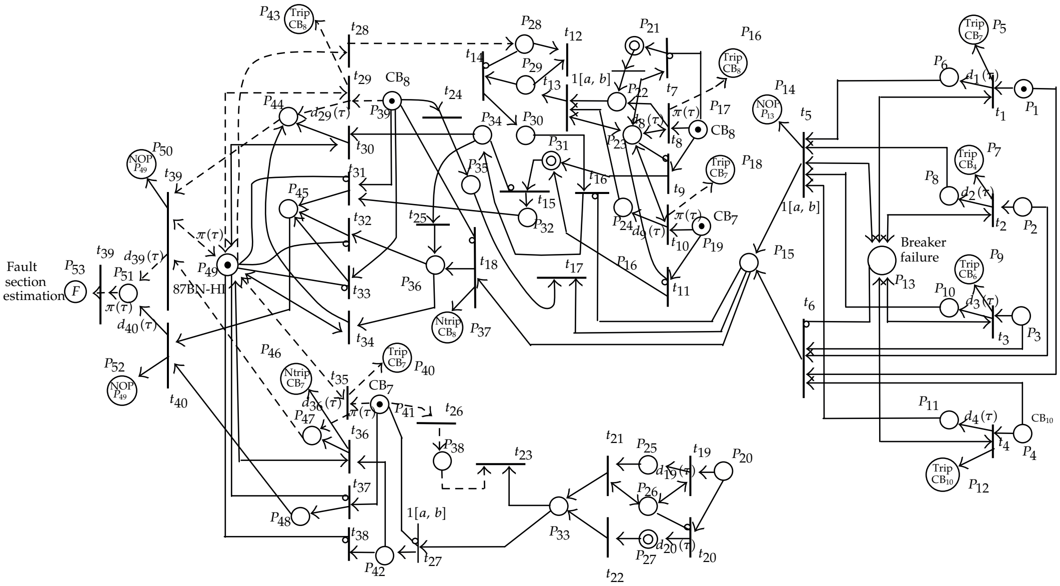

Figure 8: The backward FTPN model of Figure 6 for fault at 275 kV north busbar of Kapar substation. The marking state of FTPN indicates the postfault condition. Places P_{49}, P_{23}, P_{26}, and P_{13} correspond to main, local backup, remote backup, and breaker-failure relay, respectively. Token in place P_{49} indicates that the main relay (87BN HI) has been operated and its signal has been received. Receiving signal from circuit breaker CB_8 is shown by a token in places P_{17} and P_{39}. Receiving signal from circuit breaker and CB_7 is shown by a token in places P_1, P_{19}, and P_{41}. The broken lines are the routes of the FTPN in its firing sequences.In the case of tripping circuit breakers, places designated by trip CB_X get token, and in the case of nonoperation of any CB, places the indicated by Ntrip would get token. OP P_{49} means that the main relay has operated and NOP P_{49} means otherwise. Transitions t_{12}, t_{17}, and t_{23} are sink transitions and would fire if the main relay and breakers CB_8 and CB_7 have operated, respectively.

drawbacks of the previously reported model-based systems. This is because this proposed system gets the advantages of some powerful tools and concepts for designing real-time systems such as Petri net for modeling parallel processing and power of fuzzy set theory to handle uncertainty and imprecision. This system is able to handle parallel processing, therefore reducing the inference processing time. On the other hand, it uses the timestamps of circuit breakers (CB) and relays, which causes the fault hypotheses to be reduced accordingly. Moreover, the uncertain information from CB*s* and relays is handled by this system, therefore causing the diagnosis of the faulted section area to be more precise.

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