Rule-Expert Knowledge-Based Petri Net Approach for Distribution System Temperature Adaptive Feeder Reconfiguration

Ying-Chun Chuang, Yu-Lung Ke, *Member, IEEE*, Chao-Shun Chen, *Member, IEEE*, and Yuan-Lin Chen

***Abstract*-- This study presents a novel inference mechanism to determine appropriate switching operations by rule-expert knowledge-based Petri net (RKPN) approach. A practical distribution system with 26 feeders is specified to reveal the effectiveness of the developed methodology with computer simulations. The proposed inference mechanism can successfully solve feeder overload/fault contingency based on the load variations resulting from temperature rises.**

***Index Terms*-- rule-expert knowledge-based Petri net (RKPN), switching operation, load transfer, feeder reconfiguration, load balance, service restoration, temperature sensitivity.**

I. Introduction

Figure 1 illustrates the spinning reserve in Taiwan in the past few years, revealing steady load increases owing to the common usage of air conditioners following temperature rises in hot summer. Power consumption in Taiwan rises by approximately 650 MW/°C at temperatures above 28°C, power consumption reached 27120 MW between 1 and 2 PM on 25 June 2002, creating a new record and lowering the peak load spinning reserve to about 3.5 %. Figure 2 shows the corresponding loading factor of main transformers in Taiwan Power Company (Taipower) in 1999, indicating that 122 main transformers exceed 95%, among which 33 main transformers were overloaded.

The distribution feeders and main transformers serving commercial and residential customers in urban regions become overloaded in the summer because the load increases steeply as more air conditioners are used. A load survey study undertaken by Taipower indicates that air conditioners account for over 35% of the system peak load. The difference between the system peak and the off-peak loading in the summer increased from 4577 MW in 1989 to 9995 MW in 2003. Distribution substations in urban regions frequently become overloaded, forcing Taipower to implement an interruptible load control program to lower system peak load and prevent possible generation shortages.

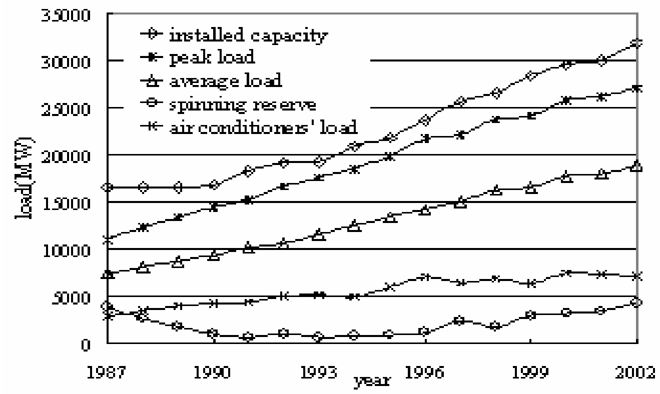

Fig. 1. The load data of Taipower system

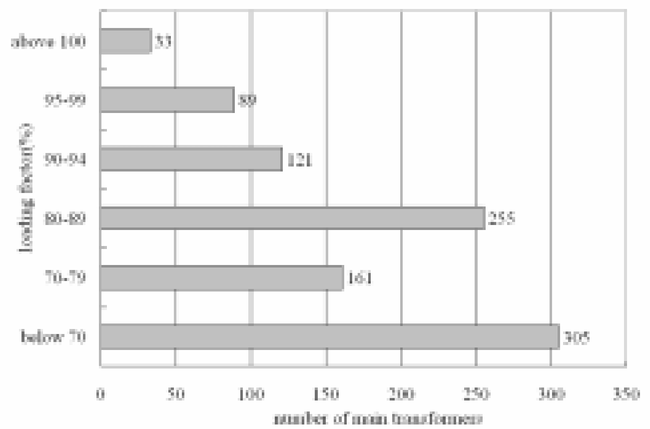

Fig. 2. Loading factor of main transformers in Taipower

Many of Taipower's feeders and main transformers are loaded near their rated capacities during the summer peak period. The reconfiguration of the feeders is a complex combinatorial and constrained optimization problem since the number of potential switching combinations is very large. Accordingly, the system is difficult to reconfigure when only using the experience of distribution operators. A systematic operation and computer decision support strategy needs to be implemented for fast and effective reconfiguration.

Automating distribution helps the operator quickly make appropriate decisions regarding the switching operations [1-7]. The daily load profile of the examined distribution feeders can

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be found from the practical load profiles, using the outage management information system (OMIS) and the customer information system (CIS). The inference mechanism based on the RKPN method integrating the operation rules with parallel-like inference characteristics is employed to find appropriate combinations of switching operations for solving the overload/fault contingencies.

Petri net (PN) is a highly effective graphical modeling approach, which has been successfully applied in scheduling restoration activity [8], estimating fault sections [9], rule-based evaluation [10] and protecting the power system [11]. This work constructed the proposed RKPN-based switching operation inference mechanism to run the appropriate feeder reconfiguration for transferring loads among the distribution feeders and the main transformers to enhance the operating performance by including utility operation rules.

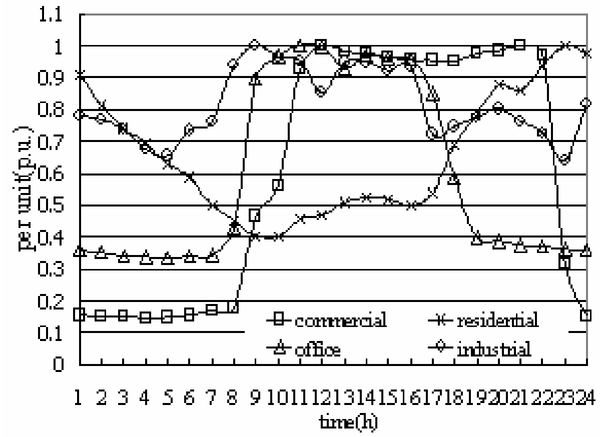

Fig. 3. Typical load patterns in Taipower

II. LOAD CHARACTERISTICS

A load survey was conducted to identify the typical load patterns of residential, industrial and commercial customers, and thus provide valuable information for operating and planning a power system. The load profile of the distribution system is a function of the customers served. Residential, commercial and industrial loads have very different daily and seasonal load profiles. The load profiles vary among distribution feeders due to the dispersion and mixture of customers served. Figure 3 shows the typical load patterns of various customers in Taipower. All customers served by the distribution feeder and the main transformer are identified, and their monthly energy consumption is obtained by the CIS.

III. TEMPERATURE SENSITIVITY ANALYSIS [12-16]

The rise in power consumption due to temperature increase varies according to the customer. A specified customer's power consumption can be denoted by a polynomial function of temperature by regression analysis. Figure 4 displays the normalized power consumption of a residential customer in Taiwan [16], for which the corresponding regression model is obtained by performing statistic regression analysis with a quadratic function of temperature, as demonstrated in Eq. (1). The rise in power consumption for each class of customer due to temperature increases is calculated from the temperature sensitivity (TS) and the daily load composition.

$$P_n = \alpha + \beta T_n + \gamma T_n^2 \quad (1)$$

where P_n denotes the normalized power consumption; T_n represents the normalized temperature, and α, β, and γ denote the coefficients of the proposed regression model.

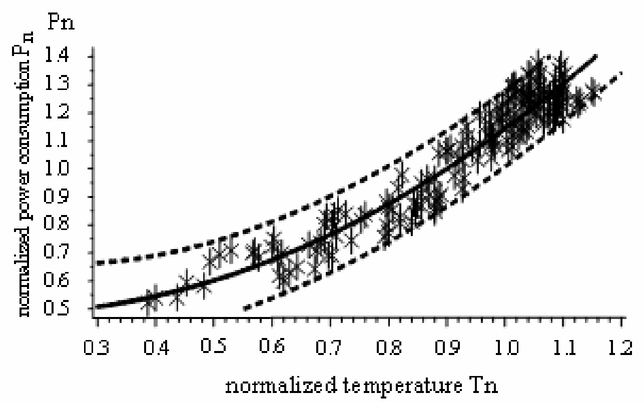

Fig. 4. The power consumption of a test residential customer vs. temperature

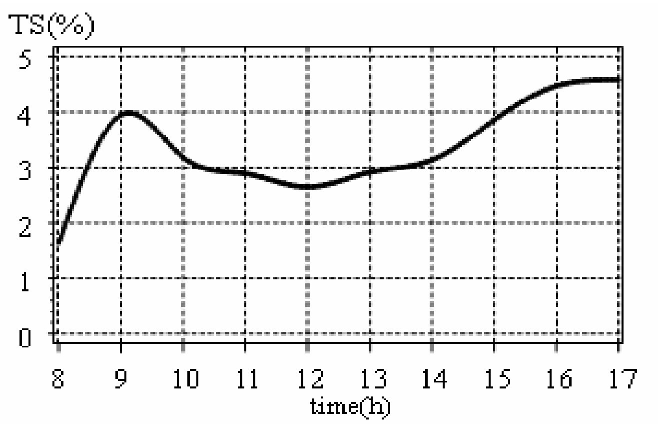

Fig. 5. Temperature sensitivity tendency for mixed customers

The temperature sensitivity (TS) of power consumption for each customer type is computed from Eq. (2) by differentiating the load models in Eq. (1) with respect to the temperature, and the rise in customer power consumption for a temperature rise of 1°C is derived by using Eq. (3). Figure 5 reveals that TS of power consumption for mixed customer in Taiwan is obtained by calculating the derivative of power consumption with respect to the temperature. Figure 6 depicts the TS of power consumption for four customers during daytime period in summer [16].

$$TS = \frac{\partial P_n}{\partial T_n} = \beta + 2\gamma T_n \quad (2)$$

$$\Delta P = TS \times \frac{P_{mean}}{T_{mean}} \quad (3)$$

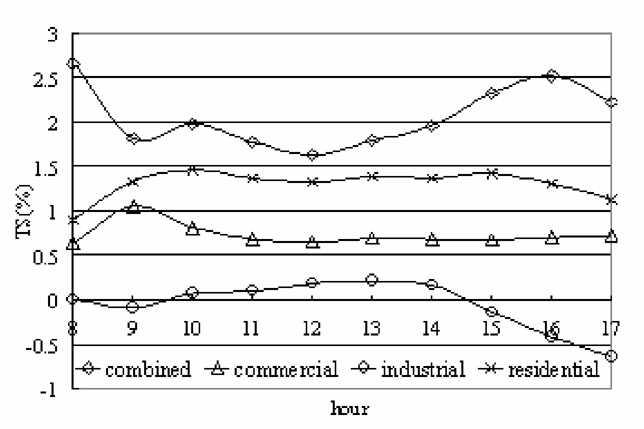

Fig. 6. Typical temperature sensitivity for various customers

IV. Rule-Expert Knowledge-Based Petri Net and Inference Mechanism for Switching Operations

Rule-Expert Knowledge-Based Petri Net (RKPN)

A. Knowledge-Based Petri Net (KPN) [17-18]

The knowledge-based Petri net is a novel extension of the Petri net (PN) and is defined as an eight-tuple with ***KPN*** = (***P***, ***T***, ***I***, ***O***, ***F***, ***M***, K_P, K_T)[17-18], where

P = $\{P_1, P_2, P_3, \dots, P_n\}$, a finite set of place nodes.

T = $\{T_1, T_2, T_3, \dots, T_m\}$, a finite set of transition nodes, where ***P*** and ***T*** are disjoint, i.e. $P \cap T = \Phi$ and $P \cup T \neq \Phi$.

I: $P \times T \to N$ is the input function, which describes the mapping from transition nodes to sets of place nodes, where ***N*** denotes the set of nonnegative integers.

O: $P \times T \to N$ is the output function, which maps transition nodes to sets of place nodes.

$F \subseteq (P \times T) \cup (T \times P)$ is the set of directed arcs.

M: $P \to N$ is a marking, which maps place nodes to the nonnegative integers ***N***. $M(p)$ is the number of tokens on place node p under the marking ***M***.

K_P: $P \to S_P$ is a one-to-one mapping from the set of place nodes ***P*** to prediction set S_P.

K_T: $T \to S_R$ is a one-to-one mapping from the set of transition nodes ***T*** to the set of rules S_R.

A KPN consists of two parts a KPN graph and its knowledge annotations. A KPN graph is similar to the conventional PN graph, and graphically denotes RKPN structures to visualize the reasoning rules. The knowledge annotations comprise the place knowledge annotations K_P and the transition knowledge annotations K_T. The place knowledge annotations that describe the tokens and facts of the place in the set of place nodes ***P***. The transition knowledge annotations form the knowledge for the transition firing rule. The knowledge annotations can be structured into a knowledge database, and the RKPN can be regarded as a knowledge-based expert system [17-18].

A place node p denotes an input node of a transition node t ($^\bullet t$) represented by $p \in I(t)$ and p is an output node of a transition node t ($t^\bullet$) represented by $p \in O(t)$. The symbol #(p, I(t)) denotes the number of occurrences of the input place node p of transition node t, and also #(p, O(t)) denotes the number of occurrences of output place node p associated with transition node t. Figure 7 depicts a typical PN with five place nodes, four transition nodes and ten arcs. The number of tokens in the place nodes determines the execution of the PN based on the knowledge of transition firing rules. A transition node is fired by removing all enabling tokens from its input place nodes and adding one token to its output place nodes. A transition node $t \in T$ in a marked PN with marking **M** is enabled if and only if $\forall p \in {}^\bullet t$: $\mathbf{M}(p) \geq \#(p, I(t))$. If $\mathbf{M}[t\rangle$, then the transition t may occur or fire, yielding a new marking $\mathbf{M}'$($\mathbf{M}[t\rangle\mathbf{M}'$] as follows [19-23].

$$M'(p) = \begin{cases} M(p) - \#(p, I(t)) + \#(p, O(t)) & \text{if } p \in {}^\bullet t \cap t^\bullet \\ M(p) - \#(p, I(t)) & \text{if } p \in {}^\bullet t \setminus t^\bullet \\ M(p) + \#(p, O(t)) & \text{if } p \in t^\bullet \setminus {}^\bullet t \\ M(p) & \text{otherwise} \end{cases}$$

for all $p \in P$.

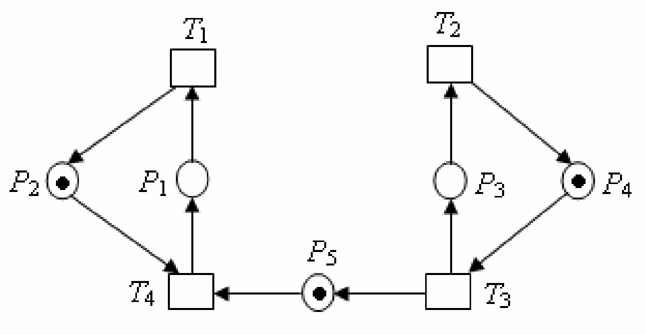

Fig. 7. A typical Petri net

B. Inference in the RKPN [19-23]

For a practical system, RKPN is utilized to model the occurrence of various events and activities in the system. The RKPN system describes the state transition of the system, in which the place nodes denote conditions, and transition nodes represent events. The RKPN inference mechanism can be implemented by passing the token from the initial state of the system to the final solution state. The transition node is enabled if each place node that enters a transition node is associated with a token. A guard function attached to a transition node represents the firing priority in the enabled transition set. Only the highest-priority transition is fired in each inference cycle. The transition node is activated if the guard function of the enabled transition node is found to be linked with the requirement to take action. The activated transition node can be fired and the tokens passed from the transition's entering places to its outgoing places. When the place node marks task completion by receiving a token, the inference process is made accordingly.

Several tokens may exist in the RKPN, simultaneously activating several transition nodes. Hence, tokens can be passed in many paths simultaneously, producing parallel-like inference.

Figure 8(a) illustrates the KPN model for the switch-open operation to release the objective zone z1, and Fig. 8(b) depicts the KPN model for the switch-open operation to release the objective zone z2. Figure 9(a) displays the KPN model for the switch close operation to pick up the objective zone z1, and Fig. 9(b) illustrates the KPN model for the switch close operation to pick up the objective zone z2.

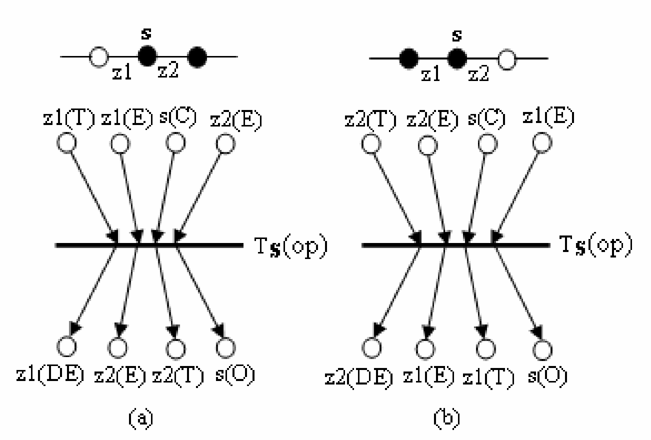

Fig. 8. KPN models for switch open operation

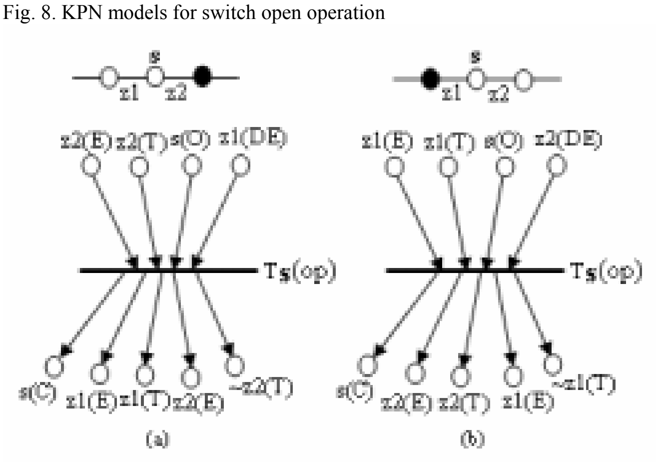

Fig. 9. KPN models for switch close operation

C. Knowledge representation models in the RKPN

The KBPN integrates the traditional PN graphical method with rapid parallel-like reasoning by adopting the "If… then…" expert rule to develop a knowledge database. The five basic models for representing knowledge are described as follows.

(1) Model type I**:** If P_i, then P_j. Figure 10 displays the structure of represented knowledge.

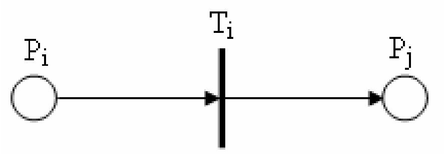

Fig. 10. Model type I for RKPN knowledge representation

(2) Model type II**:** If P_{i1}, and P_{i2}, and …and P_{in} , then P_j. Figure 11 shows a diagram of model type II.

(3) Model type III**:** If P_i , then P_{j1}, and P_{j2}, and … and P_{jn}. Figure 12 presents model type III.

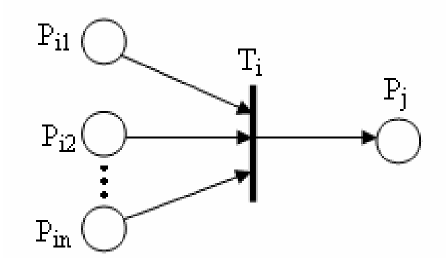

Fig.11. Model type II for RKPN knowledge representation

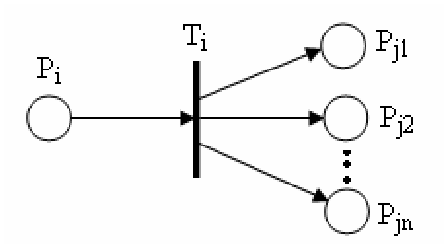

Fig. 12. Model type III for RKPN knowledge representation

(4) Model type IV**:** If P_{i1}, or P_{i2}, or …or P_{in} , then P_j. Figure 13 shows model type IV.

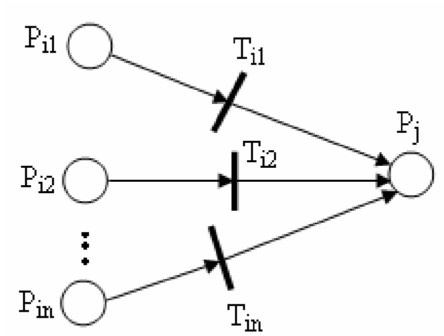

Fig. 13. Model type IV for RKPN knowledge representation

(5) Model type V**:** If P_i , then P_{j1}, or P_{j2}, or … or P_{jn}. Figure 14 displays model type V.

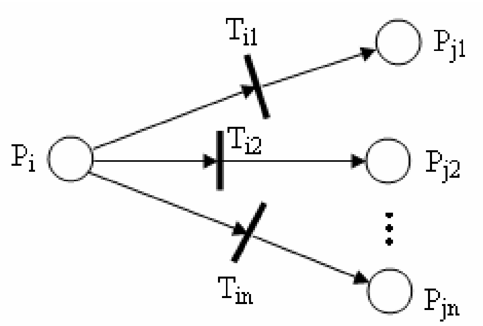

Fig. 14. Model type V for RKPN knowledge representation

Rules for switching operations

The following operation rules are applied.

Rule 1. All switches in the out-of-service areas are opened first. All terminal zones in the overloaded feeders are considered as candidate objective zones.

Rule 2. A switch that connects an unfaulted but out-of-service zone to an energized zone is treated as a candidate switch for the switching operation.

Rule 3. A switching operation can release only one objective zone and transfer its loading to an adjacent feeder. A switching operation can pick up only a single candidate object zone, and maintains the radial structure of the power distribution system once the switching operation has been performed.
Rule 4. If several candidate objective zones are to be considered for release, then the higher service priority (HSP) objective zones are disconnected at the lowest priority and restored at the highest priority.
Rule 5. If several switch candidates are present, then the switch that has the heaviest loading and is closest to the feeder outlet is considered. If several candidate objective zones are present, then the candidate objective zones with the lowest loading is specified to prevent the feeders from overloading after the switching operation has been executed.
Rule 6. If no candidate switch is present, then no feasible switching operation is found and the inference process is terminated.

V. COMPUTER SIMULATIONS

The C++ object-oriented programming language was applied to build the object-oriented database of switches, feeders and main transformers, and the RKPN-based inference mechanism combining the operating rules. Figure 15 illustrates a flowchart of the conceptual abstract algorithm for the overall solution process.

Figures 16–17 display the PN graphs corresponding to the inference process in a sample distribution system. The loadings of z1, z2 and z3 in Fig. 16 are 30A, 20A and 50A respectively. The rated current of each feeder is 60A, and feeder #2 is slightly overloaded. The switching operation (s2, s1) solves the overloading by opening switch s2 and closing switch s1. The loading of feeder #1 and #2 are both 50A after the switching operation, and the feeder overload is managed successfully. Table 1 presents the token passing during the entire inference process. A distribution system with 26 feeders is specified for computer simulations to demonstrate the effectiveness of the proposed RKPN-based inference mechanism to manage the overloaded/fault contingencies. Figure 18 shows a one-line diagram of the studied system, serving various customers, where the rated current in each feeder is 350A. Figures 19–20 depict original load profiles, and Figs 21–22 show the corresponding temperature sensitivity data of the distribution feeder. The regression model is $Pn = 0.94 - 1.45\ Tn + 1.70\ Tn^2$.

Case A*. *Multi-feeders overloading contingency

Figures 23–24 display load profiles of the distribution feeders with variation due to temperature increase. Distribution feeder #2 is slightly overloaded by 14A at 9 a.m. and 5A at 4 p.m.; #4 is overloaded by 20A at 4 p.m. and 21A at 5 p.m.; #3 is overloaded by 7A at 4 p.m. and #7 is overloaded by 26A at 4 p.m.. The multi-feeders overload contingency of feeders #1, #2, #3 and #7 is overcome from 9 a.m. by the proposed switching operations (s3, s4), (s8, s9), (s13, s14) and (s31, s32). Switch s3 is opened and switch s4 is closed to transfer the load of z4 from feeder #1 to feeder #13; switch s31 is opened and switch s32 is closed to transfer the load of z32 from feeder #7 to feeder #12. Figure 25 depicts the updated feeder configuration, and Figs. 26 and 27 display the corresponding feeder loadings after the proposed switching operations. The loading of feeder #1 at 9 a.m. was lowered from 314A to 236A, and that of feeder #2 at 4 p.m. was decreased from 320A to 264A. The multi-feeder overload problem during the daytime was thus fully resolved.

Table 1. Token-passing in each iteration process

Iteration	Black-token PL nodes	Enabled TR nodes	Fired TR node
1	P2, P3, P6, P8, P9, P12, P15, P17, P18, P20, P21	T2, T9, T17	**T9**
2	P2, P3, P5, P8, P9, P12, P15, P17, P19, P21, P23	T2, T8, T11, T14	**T8**
3	P2, P4, P5, P8, P9, P12, P15, P18, P20, P21, P23	T6, T14, T17	**T17**
4	P2, P4, P5, P8, P9, P12, P15, P18, P20, P21, P23, P24	Goal	

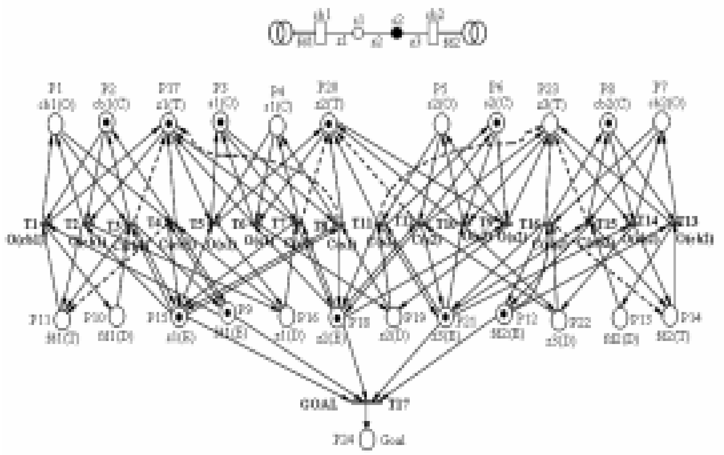
Fig.16. A simple distribution system and the corresponding Petri net graph

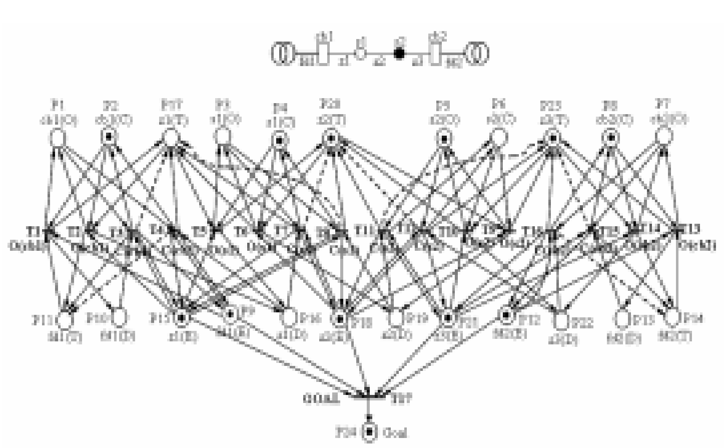
Fig. 17. The corresponding Petri net graph after firing the transition T17

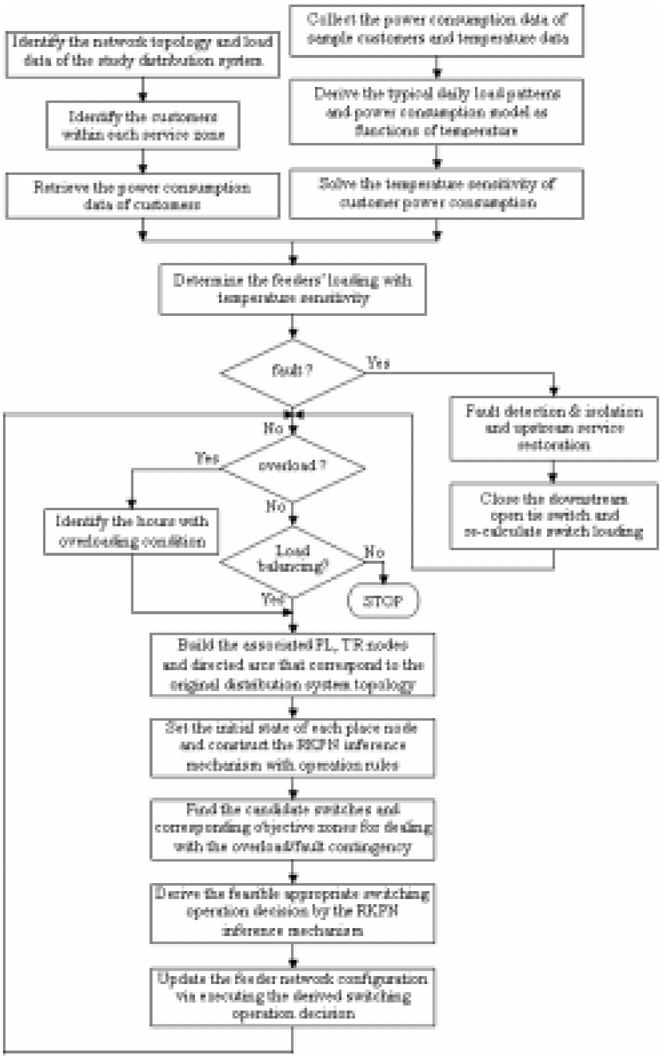

Fig. 15. The conceptual abstract algorithm for overall solution process for temperature adaptive feeder reconfiguration switching operations solution process

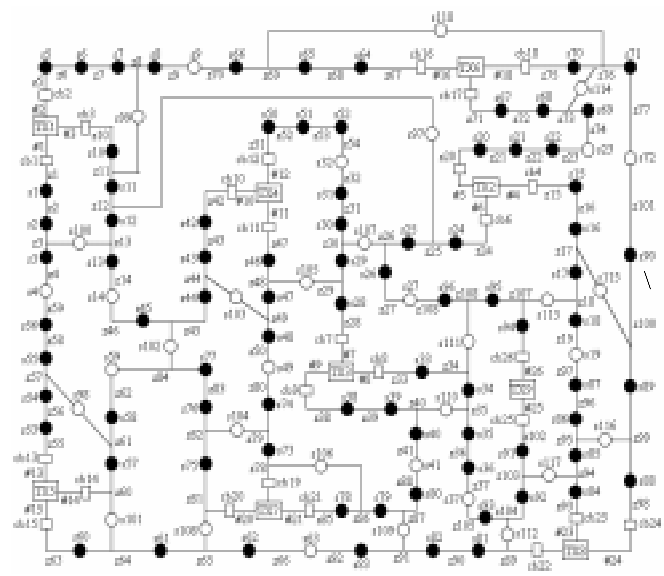

Fig. 18. One-line diagram of the study distribution system

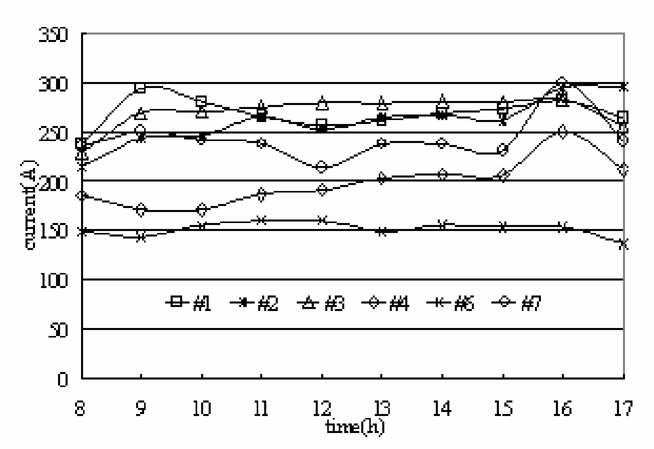

Fig. 19. Original load profiles of distribution feeders

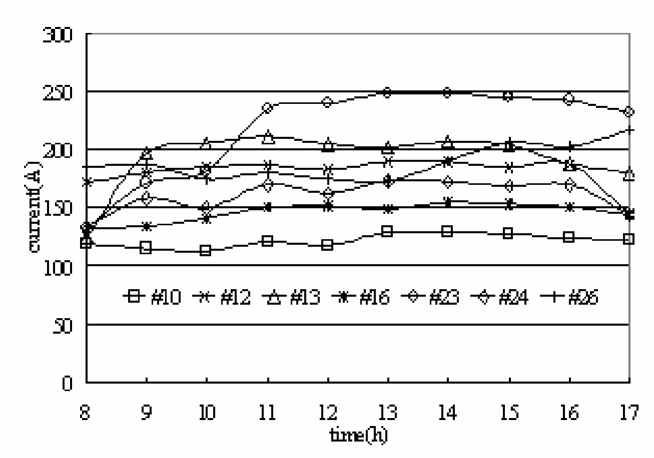

Fig. 20. Original load profiles of distribution feeders

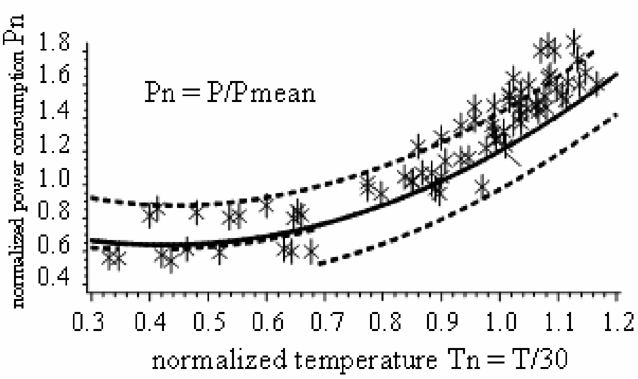

Fig. 21. The regression model for combined customers in northern Taiwan at 2 p.m.

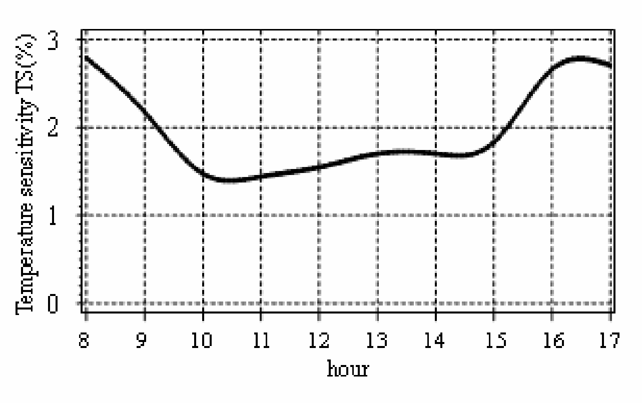

Fig. 22. Hourly temperature sensitivity tendency

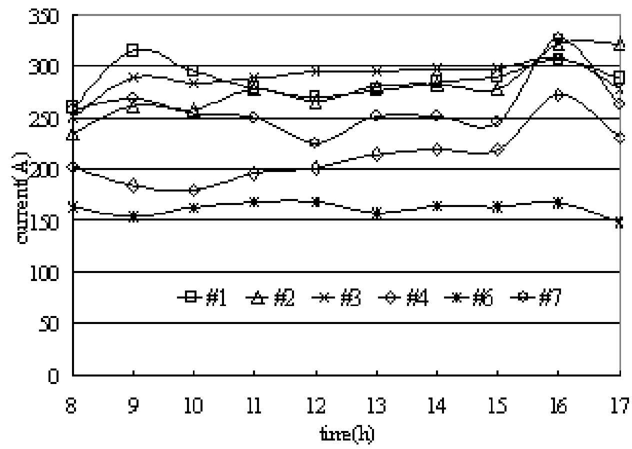

Fig. 23. Feeder load profiles with TS

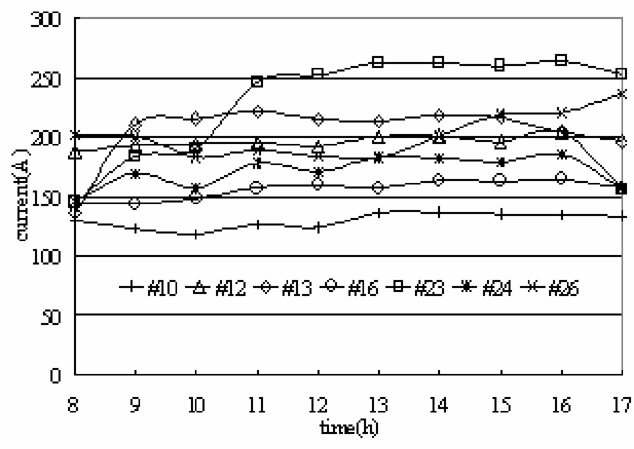

Fig. 24. Feeder load profiles with TS

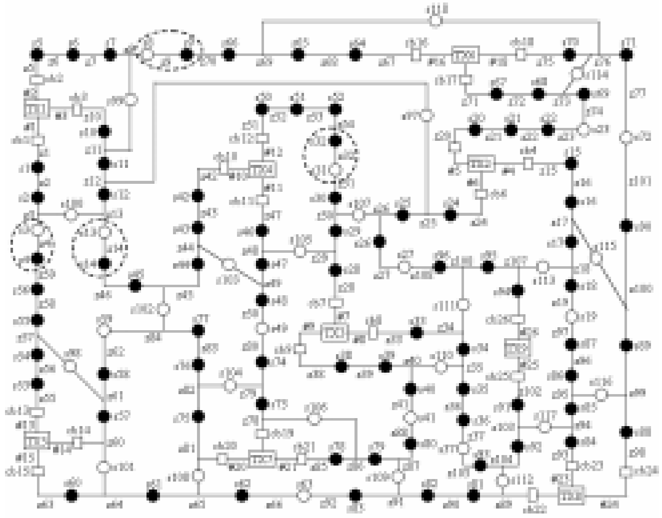

Fig. 25. Updated feeder configuration for solving multiple feeder overloads

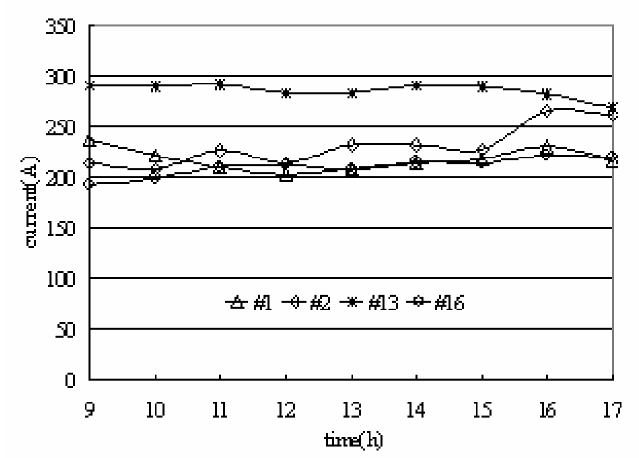

Fig. 26. Updated feeder profiles after solving overloads

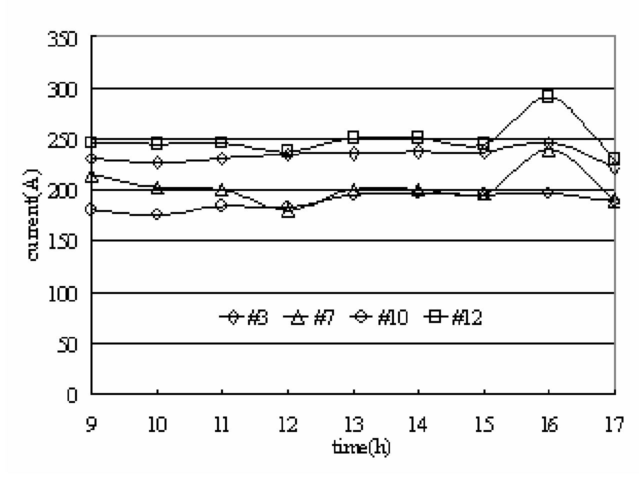

Fig. 27. Updated feeder profiles after solving overloads

Case B. Overload and Fault Contingencies

The circuit breaker of feeder #4 is tripped on the assumption that a fault occurred in zone z16 in Fig. 18 at 9 a.m., as shown in Fig. 18. Therefore, the line switches s15 and s16 connected to z16 were locked to isolate the fault area. The cb4 is then closed to restore the upstream power service of feeder #4. The proposed switching operations are then utilized to manage the overload and fault contingencies by conducting switching operations (s3, s4), (s17, s115), (s18, s113) and (s18, s19), thus solving the overload of feeder #1 at 9 a.m.. However, feeder #23 generated a overload of 5A at 1 p.m. to 18A at 4 p.m. after the switching operations for service restoration were undertaken. Figure 28 illustrates the updated configuration of the feeders, and Fig. 29 displays the updated load profiles.

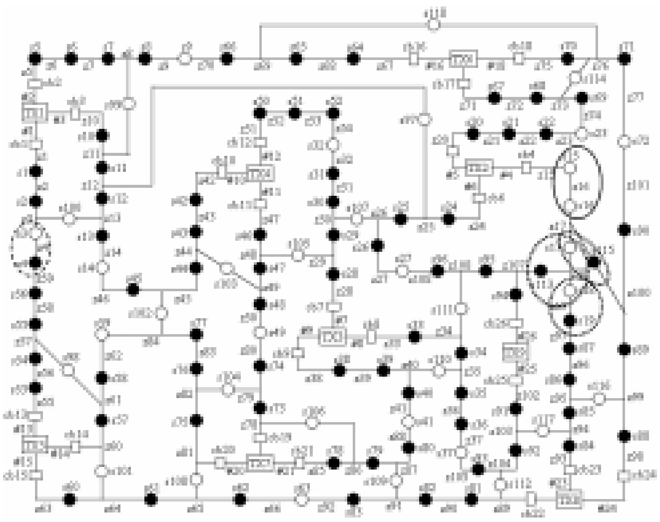

Fig.28. Feeder configuration at 9 a.m. for solving feeder fault & overload contingencies

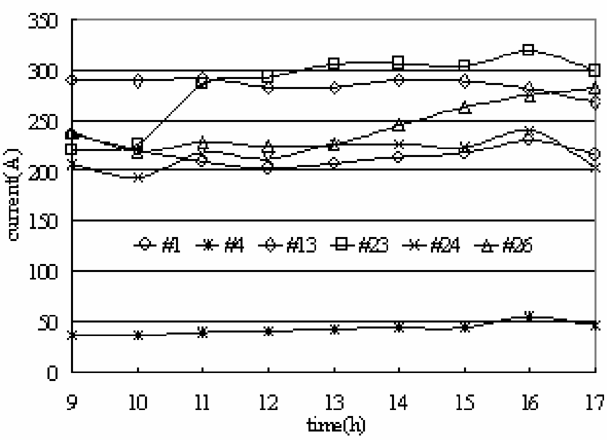

Fig. 29. Updated feeder profile after solving the fault

Switch s19 is opened and switch s18 is closed at 1 p.m. to transfer the load of z19 to feeder #26 and minimize the overloading of feeder #23 resulting from the above service-restoring switching operations. The loading of feeder #23 at 1 PM was lowered from 305A to 262A, and the overloading of feeder #23 from 1p.m. to 4 p.m. was settled. However, resolving the overload of feeder #23 but generates a further problem of the overloading of feeder #26 at 3−5 p.m.. The overloadings of feeders #2, #3, #7 and #26 at 3−5 p.m. are resloved by executing the switching operations (s31, s32), (s8, s9), (s13, s14), and (s96, s27) at 3 p.m.. Figure 30 illustrates the updated feeder configuration. The loading of feeder #2 at 4 p.m. is reduced from 320A to 264A, and that of feeder #7 at 4 p.m. is lowered from 326A to 239A. Figures. 31 and 32 displays the updated load profiles following the proposed switching operations.

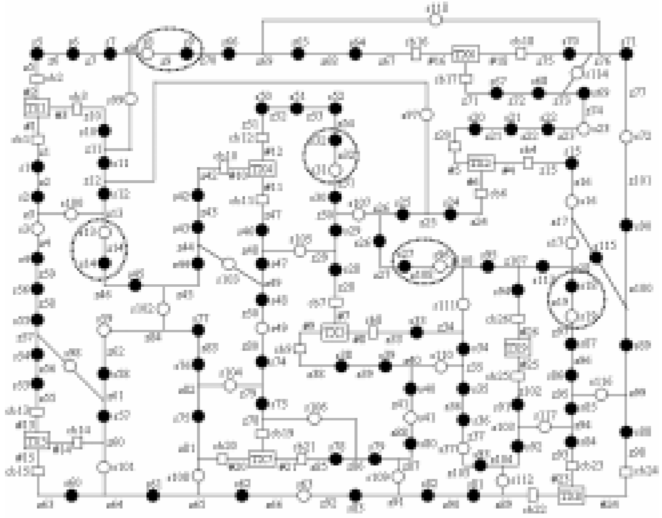

Fig.30. Feeder configuration from 1 p.m. for solving multiple feeder overloads

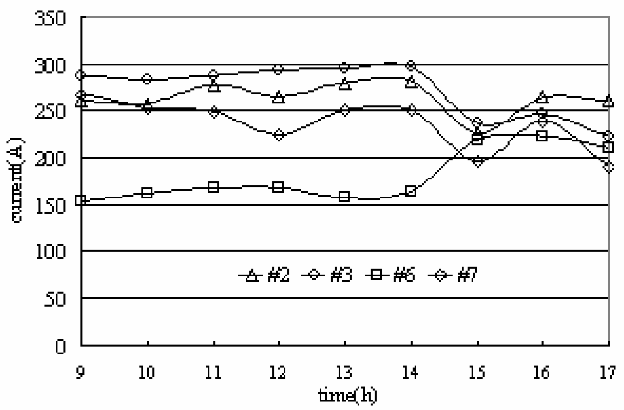

Fig. 31. Feeder loading after solving multi-feeder overloads

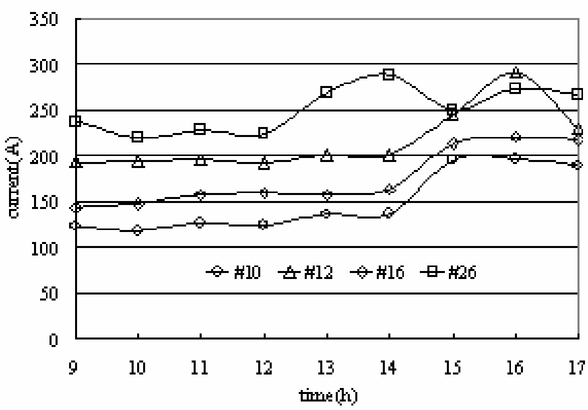

Fig. 32. Feeder loading after solving multi-feeder overloads

VI. CONCLUSIONS

This work determines the appropriate switching operations for solving the feeder overload/fault contingency by employing the RKPN-based inference mechanism. Typical load patterns, energy consumption and temperature sensitivity data from various customers were adopted to calculate the hourly loading of the service zones and distribution feeders. A distribution system containing 26 feeders and serving the mixed loads of various customers was utilized for computer simulations to show the effectiveness of the proposed methodology. The computer simulations demonstrate that the presented approach is appropriate for distribution system engineers to manage the system contingency.

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