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Power Distribution System Switching operations using Knowledge Based Colored Petri Net

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Abstract: This paper, attempts to find optimal switching operations for the service restoration and feeder load balancing of power distribution systems during normal operating condition and during contingency using Colored Petri Nets (CPN). Heuristic rules combined with the artificial intelligent Colored Petri net are applied to find the proper switching operation decision to solve the issue during a contingency. The Colored Petri Net approach performs very efficiently by its parallel like inference characteristics to determine the appropriate switching operations for solving the contingencies of distribution system. An unbalanced three phase system is studied and the satisfactory results are obtained by this method.

***Index Terms* - Radial distribution system (RDS), Colored Petri Net (CPN), reconfiguration, Knowledge Based Colored Petri nets (KBCPN), Petri net (PN).**

I. INTRODUCTION

The main objective of service restoration is to restore as many loads as possible (i.e., minimize loads in out-of-service areas) by transferring de-energized loads in the out-of-service areas to other supporting distribution feeders without violating operating and engineering constraints via network reconfigurations. Network reconfiguration is the process of altering the topological structures of distribution feeders by changing the open/closed status of the sectionalizing and tie switches. During normal operating conditions, networks are reconfigured for two purposes: (1) loss reduction, to reduce the system real power loss and (2) load balancing, to relieve network overloads.

In an emergency state, the system can be so arranged that a maximum number of customers retain electrical service. The reconfiguration of the feeders is a complex combinatorial and constrained optimization problem since the numbers of switching combinations are very large. Hence, it is very difficult to reconfigure the system using the experience of distribution operators alone. A systematic operation and computer decision support strategy needs to be implemented for fast and effective reconfiguration. Thus, automating the distribution system helps the operator to take appropriate decisions quickly regarding the switching operations. A branch exchange-type heuristic algorithm has been suggested by Civanlar et al. [5] where a simple formula has been derived to determine how a branch exchange affects the losses. Goswami and Basu [6] report a heuristic algorithm that is based on the concept of optimum flow pattern that is determined by using a power-flow program. The optimum flow pattern of a single loop formed by closing a normally open switch is found out, and this flow pattern is established in the radial network by opening a closed switch. This procedure is repeated until the minimum loss configuration is obtained.. The algorithm developed by Gomes et al., [7] uses a heuristic strategy that starts with the system in a meshed status, with all maneuverable switches closed. The choice of the switches to be opened is based on the calculation of the minimum total system losses, using a load-flow program. The main drawback of this method is too many iterations are involved to get the result. G.K. Viswanadha Raju & P.R.Bijwe [12] proposed a new heuristic method for determining the minimum loss configuration of a distribution network. Their method starts with a power flow solution of the system with all its switches closed. Then the switches are opened successively to restore radial configuration. This method also involves too much iteration to get the result. K L Puttabuddhi, Bijwe P R & J Nanda [11] uses linearized model without iteration. Though the method is fast in evaluating critical contingencies it is applicable only to balanced system and no restorative techniques are used.

CPN is a powerful graphical modeling method and has been successfully used in scheduling restoration activity [3], network reconfiguration [8], rule based evaluation [4] and protecting the power system.

This paper describes the inference mechanism for switching operation decisions by combining the rule expert knowledge based CPN with service operation rules for transferring loads among distribution feeders. This approach performs very efficiently because of CPN’s parallel like inference capability to determine the appropriate switching operations for solving the contingencies of distribution operations.

The organization of this paper is as follows: Section 2. Formulation of reconfiguration problem, Section 3. Knowledge based Petri net system & its inference mechanism, Section 4. Test systems, Section 5. Conclusion

II. FORMULATION OF RECONFIGURATION PROBLEM

The purpose of this paper is to determine a restoration plan for contingencies and to assist the decision makings of distribution system dispatchers for the service restoration of out-of-service area. The following objectives are considered for the service restoration.

To restore the supply to as many customers as possible within unfaulted but out-of-service area.

The customers with higher service priority will have better chance to be restored.

The service should be restored to all the customers as soon as possible with minimum number of switching operations.

To identify appropriate switching option, that results in reduction of power losses.

Radial configuration of the distribution system must be maintained after service restoration.

No components in distribution systems should be overloaded.

In a radial distribution system to achieve a maximum reduction in power loss, the aim is to identify the appropriate switching options. “CPN tools” is used for getting the information about the switches to be operated to achieve the above goal. The heuristic rules are included in the CPN model by considering the rule of thumb of system operation for load balancing. The rules have two stages to deal with load balancing: disconnection phase (DP) & pickup phase (PP). With the unbalance loading among main transformers or feeders, the switching decision making is performed to transfer partial loading of the heavily loaded transformers/feeders to the lightly loaded ones.

This algorithm is composed of two phases: disconnection phase (DP) & pickup phase (PP). In DP, service zones are disconnected from the system for the overload feeders/ main transformers.

In PP, the previous disconnected areas are restored one by one under system constraints such as radial feeder structure and feeder/transformer rating capacity.

For the solution process, DP is always executed before PP. However, another DP & PP has to be enabled if further overload occurs after the PP

Distribution operation rules

The following rules are used in DP:

Rule1: Every switching action releases the objective zone only. The objective zones are disconnected one by one. All switches in the out of service areas will be opened.

Rule2: All of the terminal zones in the overloaded feeders/ main transformers feeders are considered to be the objective zones to be released..

Rule3: If there are several objective zones the options which releases relatively small load & will result in system rating after the operation is selected.

Rule4: If there are several objective candidates, the HSP objective zones have less priority to be disconnected.

In PP, the following rules are used:

Rule5: Every switch connected between an energized zone & a healthy but isolated zone is a candidate switch.

Rule6: Pickup only one service zone for each switching operation. Radial feeder structure can be assured.

Rule7: If there are several switching candidates, the option that is close to the feeder outlet & will pick up relatively heavy loading is selected.

Rule8: The switching candidate that was closed before contingency will be selected with higher priority. This rule is to find the solution with minimum number of switching.

Rule9: If there are several objective candidates, the HSP objective zone will be restored first.

III. KNOWLEDGE BASED COLOURED PETRI NET SYSTEM (KBCPN) & ITS INFERENCE MECHANISM

Knowledge–based Coloured Petri net may be built upon the extention of of the basic place–transition Petri nets and incorporation with the knowledge base. It is defined as an eight tuple with ***KBCPN* = (*P,T,I,O,F,M,K$_P$,K$_T$*)**, where

P = {P$_1$, P$_2$, P$_3$ ... P$_N$} is a finite set of place nodes.

T = {T$_{1,}$ T2, T3$_{...}$ T$_N$} is a finite set of transition nodes where ***P*** and ***T*** are disjoint, i.e., $P \cup T = \Phi$ and $P \cap T \neq \Phi$

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

O* : *P* × *T* → *N is the output function, which maps transition nodes to sets of place nodes.

F ⊆ (***P*** × ***T***) ∪ (***T*** × ***P***) is the set of directed arcs.

M* : *P*→ *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*→ *S$_P$ is a one to one mapping from the set of place nodes ***P*** to prediction set ***S$_P$***.

K$_T$* : *T*→ *S$_R$ is a one to one mapping from the set of transition nodes ***T*** to the set of rules ***S$_R$***.

A KBCPN consists of two parts: a KBCPN graph and its knowledge annotations. A KBCPN graph is similar to the conventional PN graph and graphically denotes KBCPN structures to visualize the reasoning rules. The knowledge annotations comprise the place knowledge annotations KP and the transition knowledge annotations ***K$_T$***. The place knowledge annotations describe about 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 KBCPN can be regarded as a knowledge –based expert system.

i Enabled Transition Node

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*. 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 $\forall_p \in^{\bullet} t : M(p) \geq \#(p, I(t))$. If, $M[t>$, then the transition *t* may occur or fire, yielding a new marking $M'(M[t>M']$ as follows:

$$M'(p) = \begin{cases} M(p) - \#(p, I(t)) + \#(p, O(t)), & \text{if } p \in {}^{\bullet}t \cap t^{\bullet} \\ M(p) - \#(p, I(t)), & \text{if } p \in {}^{\bullet}t \setminus t^{\bullet} \\ M(p) + \#(p, O(t)), & \text{if } p \in t^{\bullet} \setminus {}^{\bullet}t \\ M(p) & \text{otherwise} \end{cases} \tag{1}$$

ii Inference in the KBCPN

For a practical system, KBCPN is utilized to model the occurrence of various events and activities in the system. The KBCPN system describes the state transition of the system, in which the place nodes denote conditions, and transition nodes represent events. The KBCPN 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 KBCPN, simultaneously activating several transition nodes. Hence, tokens can be passed in many paths simultaneously, producing parallel-like inference.

iii Building of CPN Models

The knowledge base of feeders, switches, circuit breakers, zones and transformers are built using CPN modeling language. Each condition is modeled as places. The conditions for feeders are set considering the maximum current rating specified for the feeders. The integer colour sets are used for this declaration. The conditions for zones are set as energized, de-energized, terminal and not-terminal. Colours for these conditions are declared as E (energized), DE (de-energized), T (terminal) and NT (not-terminal). For switches and circuit breakers the conditions are chosen based on open and closed position. Colours declared are ON for closed and OFF for open switches/circuit breakers respectively. The conditions set for transformer are similar to zone conditions.

The color set declaration for distribution system components are summarized in Table 1. The color set declared for feeders is integer, which takes any integer value. Hence that is not included in Table1.

TABLE 1: SUMMARY OF COLOR SET DECLARATION
FOR DISTRIBUTION SYSTEM COMPONENTS

Components	Colors			
Circuit breakers	ON	OFF		
Switches	ON	OFF		
Transformer	E	DE	T	NT
Zones	E	DE	T	NT
Load	E	DE	T	NT

The distribution operation rules are modeled in CPN using the if-then-else control structure. The CPN models for switch open and switch close operations are shown in Fig.1 to Fig.4 respectively.

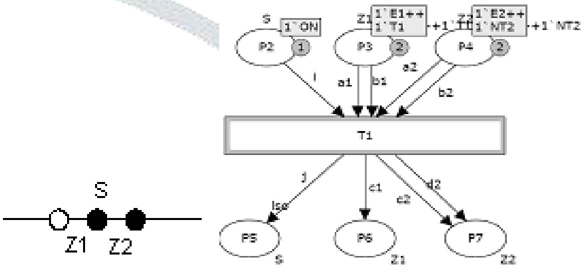

Fig.1. CPN model for switch open operation (before the firing of transition)

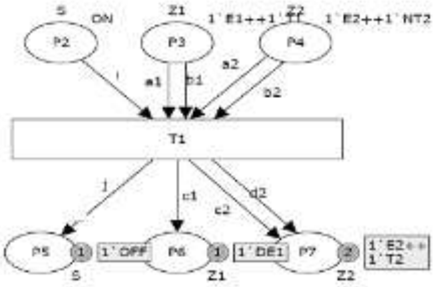

Fig.2. CPN model for switch open operation (after the firing of transition)

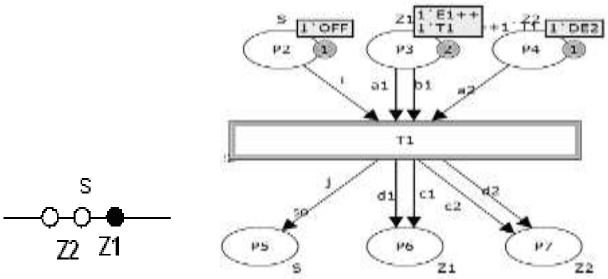

Fig.3.CPN model for switch close operation (before the firing of transition)

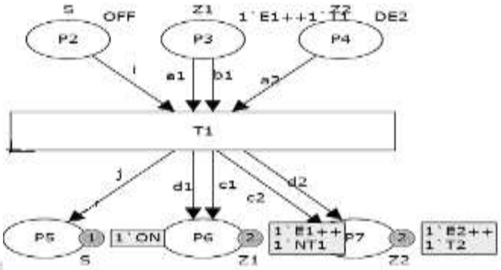

Fig.4. CPN model for switch close operation (after the firing of transition)

Table II illustrates the inferences derived for switching operations. Equations (2) to (5) explain clearly the two cases each for switch open and switch close operation. In Fig. 1, CPN model is developed to release the loading of Z1 by opening the switch S when all of the states of three input place nodes of the transition node are met: the input place Z1 is initialized with E1&T1 meaning Z1 is energized and is a terminal zone, Z2 is with E2 & NT2 meaning Z2 is energized but is not a terminal zone and S has the colour token ON indicating that the switch is closed. After the firing of transition node the output places should possess the tokens as given in equation (2). The enabled transition will fire and pass the tokens to the output places according to the “if … then…” rule included in the guard. The tokens to be passed to the output places should be DE1 for Z1 meaning Z1 is deenrgized, E2 & T2 for Z2 indicating Z2 is energized and terminal zone and OFF for S meaning the switch is open. Similarly, in Equation (3) <case 2, open> is to release the loading of Z2 by opening the switch S.

TABLE II INFERENCE OF CPN MODEL FOR
TRANSITION NODE AND PLACE NODES

S(op)	**Pre-action color Setting**			**Post-action color setting**		
	Z1	***Z2***	***S***	***Z1***	***Z2***	***S***
Case 1, open	E&T	E&NT	ON	DE	E&T	OFF
Case 2, open	E&NT	E&T	ON	E&T	DE	OFF
Case 1, close	E&T	DE	OFF	E&NT	E&T	ON
Case2, close	DE	E&T	OFF	E&T	E&NT	ON

$$\langle\text{Case 1, open}\rangle\text{: } [Z1\,(E\&T)\times Z2(E\&NT)\times S(ON)] = Z1(DE)\times Z2(E\&T)\times S(OFF)] \tag{2}$$

$$\langle\text{Case 2, open}\rangle\text{: } [Z1\,(E\&NT)\times Z2(E\&T)\times S(ON)] = Z1(E\&T)\times Z2(DE)\times S(OFF\,)] \tag{3}$$

$$\langle\text{Case 3, close}\rangle\text{: } [Z1\,(E\&T)\times Z2(DE)\times S(OFF)] = [Z1(E\&NT)\times Z2(E\&T)\times S(ON)] \tag{4}$$

$$\langle\text{Case 4, close}\rangle\text{: } [Z1\,(DE)\times Z2(E\&T)\times S(OFF)] = [Z1(E\&T)\times Z2(E\&NT)\times S(ON)] \tag{5}$$

To implement the operational rules of distribution system for service restoration, the switching sequences are prioritized. The priorities set for different rules are as tabulated in Table III. Priorities are set as follows:

High priority customers such as hospitals, police station etc, with integer value ‘0’. Next priority customers such as commercial establishments with value attached equal to ‘1’, and Low priority customers such as residential where the priority value is set to ‘2’. In CPN, the priorities can be attached to transitions along with its guard expression.

TABLE III PRIORITY LEVELS SET FOR OPERATIONAL RULES

Sl. No.	**Priority levels**	**Priority values**	**Description**
1.	P_HIGH P_MEDIUM P_LOW	0 1 2	Priorities set for the different Class of customers
2.	P_smallload P_mediumload P_heavyload	10 100 1000	Priorities set for the load to be released during disconnection phase.

In a CPN network if many transitions are enabled, then the transition with higher priority will be fired first. In CPN tools software, though all the input places of transitions have color tokens the transitions are not enabled if different priorities are set for different transitions.

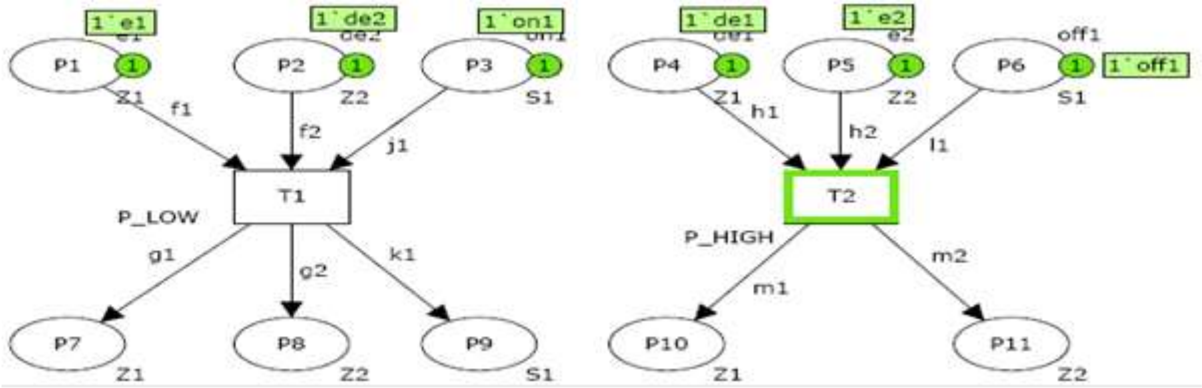

Fig.5. CPN model showing the priorities

In Fig.5 there are six input places and five output places. There are six input arcs and five output arcs. Three input arcs each from three input places are connected to transitions T1 and T2 respectively. The green aura around T2 represents that T2 is enabled. Though all the input places connected T1 also carry the color tokens, T1 is not enabled due to the low priority attached. Once T2 fires, then T1 will be enabled. This action is depicted in Fig.6.

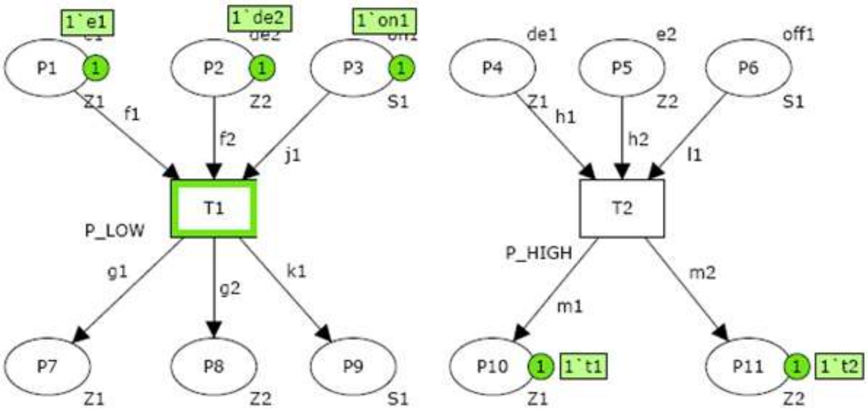

Fig.6. CPN model showing the priorities after the firing of higher priority transition

iv The switching CPN algorithm

a. Build the associated PL, TR nodes and directed arcs that correspond to the original distribution system topology.
b. Set the initial state of each place node and construct the KBPN inference mechanism with operation rules.
c. Find the candidate switches & corresponding objective zones for dealing with the overload / fault contingency.
d. Derive the feasible appropriate switching operation decision by the KBPN inference mechanism.

Update the feeder network configuration via executing the derived switching operation decisions.

IV. TEST SYSTEM

The test system is a 4.16 kV, 25 node unbalanced radial distribution system. This unbalanced RDS consists of three tie lines. The single line diagram of this system is shown in Fig.7. The base values for this system are 4.16 kV and 30 MVA. The test system consists of 22 sectionalizing switches and 3 tie switches. For the analysis by CPN, the system is divided into 54 zones. The zones are represented by small black circles, the sectionalizing switches by circles with a cross inside and tie switches by circles. For simplification, a single line diagram of Fig.7 is represented for balanced system. But the analysis is done for three phase unbalanced system.

The power flow study is done for the base case. This system consists of one main feeder and three laterals. The first lateral is connected to bus No. 2, second lateral starts at bus No. 3 and the third lateral starts at bus No. 4. The current distribution for the base case is shown in Table IV.

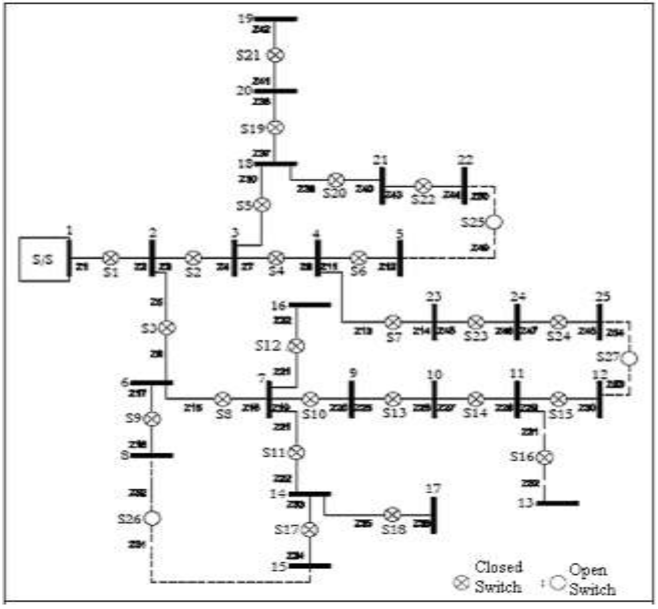

Fig.7. Single line diagram of 25 bus unbalanced radial distribution system (URDS)

It is clear that the line connected between the buses 2 and 6, i.e. first lateral carry high current. This is due to the high load connected to bus No. 15. CPN model developed for this system is executed to derive the inference. Based on the decisions derived from this method, the switches S15, S17 and S22 are opened during disconnection phase. Switches S25, S26 and S27 are closed during pick up phase to maintain the radial structure of the system. The power flow study is done with this arrangement and the current analysis is shown in Table V. It is clear from Table V that the current through the first lateral and second lateral are reduced, while through the third lateral is increased in order to balance the load among the laterals. Also slight change in voltage profiles is observed as shown in Table VI.

TABLE IV CURRENT ANALYSES OF 25 BUS URDS (BASE CASE)

From To bus	**$\lvert I_R \rvert$ in A**	**$\lvert I_Y \rvert$ in A**	**$\lvert I_B \rvert$ in A**
1-2	328.3590	332.1770	331.8723
2-3	154.2825	155.0217	153.7914
3-4	75.3307	74.2494	69.4908
4-5	12.2549	12.2710	12.2627
2-6	**174.0776**	**177.1622**	**178.0820**
6-8	12.2662	12.2834	12.2773
6-7	149.5569	151.3308	155.2550
7-16	12.3257	12.3463	12.3402
7-14	68.6212	67.7502	73.4652
14-17	12.3557	10.6467	13.6643
14-15	41.1967	41.2701	41.2539
7-9	68.6133	71.2348	69.4497
9-10	50.0927	55.4003	54.3631
10-11	39.4497	43.0034	40.6876
11-12	10.6547	13.7090	12.4046
11-13	15.1205	18.6225	15.8869
3-18	**68.4455**	**68.5395**	**70.8087**
18-20	28.9541	27.2720	29.2695
20-19	18.4082	14.9978	15.7281
18-21	27.2437	29.0035	29.2798
21-22	14.9822	18.4396	15.7337
4-23	**47.3936**	**43.5850**	**42.2674**
23-24	28.9922	27.9012	27.2856
24-25	18.4324	14.3461	15.0053

TABLE V CURRENT ANALYSIS OF 25 BUS URDS (AFTER RECONFIGURATION)

From To Bus	**$\lvert I_R \rvert$ in A**	**$\lvert I_Y \rvert$ in A**	**$\lvert I_B \rvert$ in A**
1-2	327.9136	331.6784	331.3532
2-3	167.7112	175.0009	169.7043
3-4	101.0520	106.5396	97.7030
4-5	30.6945	28.0423	27.2799
2-6	**160.2025**	**156.6855**	**161.6494**
6-8	53.3077	53.3797	53.3555
6-7	94.6480	89.7689	97.7522

7-16	12.2951	12.3097	12.3069
7-14	27.3195	26.3620	32.0775
14-17	12.3071	10.5989	13.6071
8-15	41.0126	41.0683	41.0495
7-9	55.0347	51.0976	53.3689
9-10	36.5662	35.3187	38.3275
10-11	25.9606	22.9757	24.7005
11-13	12.3395	12.3535	12.3521
3-18	**56.1472**	**56.2229**	**58.4987**
18-20	30.6575	25.5510	29.2630
20-19	12.2673	10.5660	13.5601
18-21	14.9604	18.4130	15.7100
5-22	18.4204	15.7515	15.0002
4-23	**54.6636**	**60.0972**	**55.4461**
23-24	44.0956	46.5060	43.1505
24-25	25.6491	32.1760	28.1356
25-12	15.0517	18.5421	15.8073

TABLE VI VOLTAGE PROFILE OF 25 BUS URDS

Bus No.	**$\lvert V_R \rvert$ in p.u.**		**$\lvert V_Y \rvert$ in p.u.**		**$\lvert V_B \rvert$ in p.u.**	
	Base Case	***After Recon***	***Base Case***	***After Recon***	***Base Case***	***After Recon***
1	1.000	1.000	1.000	1.000	1.000	1.000
2	0.986	0.986	0.985	0.985	0.986	0.986
3	0.983	0.983	0.982	0.982	0.982	0.982
4	0.981	0.979	0.979	0.978	0.980	0.979
5	0.980	0.979	0.979	0.977	0.980	0.978
6	0.980	0.981	0.979	0.980	0.979	0.980
7	0.979	0.977	0.978	0.976	0.979	0.976
8	0.975	0.978	0.973	0.976	0.974	0.977
9	0.975	0.977	0.973	0.976	0.974	0.976
10	0.973	0.977	0.971	0.975	0.971	0.975
11	0.972	0.976	0.971	0.975	0.971	0.975
12	0.972	0.976	0.970	0.975	0.971	0.975
13	0.973	0.976	0.971	0.975	0.972	0.975
14	0.971	0.974	0.969	0.973	0.970	0.973
15	0.970	0.974	0.968	0.973	0.969	0.973
16	0.970	0.974	0.968	0.972	0.968	0.973
17	**0.970**	**0.974**	**0.968**	**0.972**	**0.968**	**0.973**
18	0.981	0.981	0.979	0.980	0.980	0.980
19	0.980	0.980	0.978	0.979	0.979	0.979
20	0.979	0.979	0.978	0.978	0.978	0.978
21	0.979	0.980	0.978	0.979	0.979	0.979
22	0.979	0.978	0.977	0.977	0.978	0.978
23	0.979	0.978	0.978	0.976	0.979	0.977
24	0.978	0.977	0.977	0.975	0.978	0.976
25	0.978	0.975	0.977	0.973	0.977	0.974

V. CONCLUSION

In this paper the proper switching operations to solve the problem of feeder overload condition has been derived by applying rule expert knowledge based colored Petri net mechanism. The service rules for system contingency have been included in the inference mechanism. By executing proper switching operations derived by the KBPN inference mechanism, the feeder overload problem has been solved by load transfer among the distribution feeders. According to the computer simulations, it is concluded that the proposed methodology does provide an effective tool for distribution system engineers to solve the system contingency.

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