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Performance analysis of 66/11 KV substation using Petri nets and vague lambda tau methodology

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ABSTRACT

In this paper, a new methodology named as vague lambda-tau, is proposed for reliability analysis of the repairable systems. In this methodology, vague set theory is coupled with conventional lambda-tau method to evaluate the vague expressions for OR/AND-transition of Petri nets model. This paper involves the qualitative and qualitative analysis of 66/11 KV substation system. In qualitative analysis, Petri net model is obtained from its equivalent fault tree and in quantitative analysis, reliability parameters are evaluated using vague lambda-tau methodology. By using this approach, system reliability can be analyzed in a more flexible and more intelligent manner.

Keywords: 66/11 KV substation system; vague lambda-tau methodology; fault tree; Petri nets modeling.

INTRODUCTION

Fault tree analysis (Ebeling, 2000) is a powerful diagnosis technique and is widely used for demonstrating the root causes of undesired event in system failure. The concept of FTA was developed by Bell telephone laboratory in 1961.

Fuzzy set theory (Zadeh, 1965) has been shown to be useful tool to handle the situations (in which the data is imprecise) by attributing a degree to which a certain object belongs to a set. In real life problems there may be hesitation or uncertainty regarding the belongingness of an object to a set or not. Gau & Buehrer (1993) pointed out that in fuzzy set theory, there is no means to incorporate such type of hesitation or uncertainty and proposed the concept of vague set. Chen (2003) presented the arithmetic operations between vague sets and also proposed a new method for analyzing the fuzzy system reliability based on vague sets. Kumar *et al.* (2005) presented fuzzy reliability analysis of marine power plant using vague set theory, where the reliability of components of the system is represented by trapezoidal vague sets defined on the universe of discourse $[0, 1]$. Shu *et al.* (2006) proposed an algorithm to evaluate the fault interval of the system components using vague fault tree analysis and applied this method to the failure analysis problem of Printed Circuit Board Assembly (PCBA). Chang & Cheng (2009) proposed an algorithm to evaluate the fault interval of the system components using vague fault tree analysis and applied this method to the failure analysis problem of Printed Circuit Board Assembly (PCBA). Taheri & Zarei (2011) investigated bayesian system reliability assessment in vague environment.

The FTA approach assumes that the causes of events are random and statistically independent but certain common causes can lead to correlations in event probabilities which violate the independence assumptions and could exaggerate the likelihood of an event fault. To overcome these limitations Petri nets can be conveniently used since it allows us to describe large state spaces by a restricted number of model primitives (places, transitions and tokens) (Marsan *et al.,* 1995). Hura & Atwood (1988) proposed the use of Petri nets to represent fault trees. Liu & Chiou (1997) described such a method and proposed an algorithm for generating minimal cut sets of the translated trees. Knezevic & Odoom (2001) developed new methodology which uses Petri nets instead of the fault tree methodology and solves for reliability indices utilizing fuzzy lambda-tau method. Prediction of failure in an industrial system by the use of Petri Nets and Fuzzy lambda-tau methodology was proposed by Sharma *et al.* (2008).

Rest of the paper is organized as follows: In Section 2, introduction to Petri net theory and conversion from FTA to Petri net model is presented. Section 3 introduces the basic definitions and operations of vague sets and Section 4 proposes a new approach of vague reliability and presents an algorithm to find out the vague reliability of a system. In order to illustrate the proposed approach, this paper considers an example of a 66/11 KV substation and some comparisons with the existing approaches are discussed in Section 5. The final section makes conclusions.

PETRI NETS THEORY

Overview

Petri nets are a general purpose graphical and mathematical tool for describing the relations between conditions and events. Owing to the variety of logical relations that can be represented with Petri net, it is a powerful tool for modeling system. It can be used not only for simulation, reliability analysis and failure monitoring, but also for dynamic behavior observation. This greatly helps fault tracing and failure state analysis. In the field of reliability modeling, it is demonstrated in Liu & Chiou (1997) that Petri nets are easy to implement and more effective than the traditional fault tree analysis. The determination of minimal path sets could be achieved in Petri net models without transforming the Petri net to its dual (i.e. minimal cut and path sets can be determined at the same time). Also, it was demonstrated in Liu & Chiou (1997) that for the same model, it takes about twice as much instructional steps to generate minimal cut sets in a fault tree model as in equivalent Petri net models.

System modeling using Petri net models

Similar to fault trees, graphical models based on Petri nets can be constructed to represent cause and effect relationship among events. Figure 1 is the OR/AND logic gates operations of Petri net model corresponding to the fault tree OR/AND logic gates. Figure 2 (a) is a fault tree example in which events {A,B,C,D} and {E} are basic causes of event 0. The logic relations between the events are described as well. The correlation between the fault tree and Petri net is shown in Figure 2 (b), which is the Petri net transformation of Figure 2 (a). Minimal cut and path sets can be derived from a Petri net model more efficiently than from an equivalent fault tree model. It was demonstrated through a matrix method (Liu & Chiou 1997), which shows that the determination of minimal path sets could be achieved in Petri net model without transforming the Petri net to its dual. The minimal cut sets of the Petri net model shown in Figure 2 (b) are {A,B,E,C,D}.

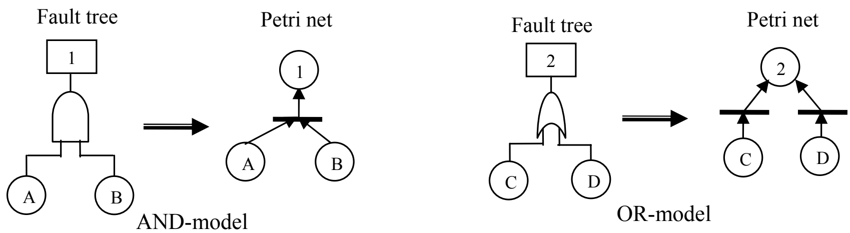

Fig. 1. Basic fault tree logic gates and their representation in Petri net model

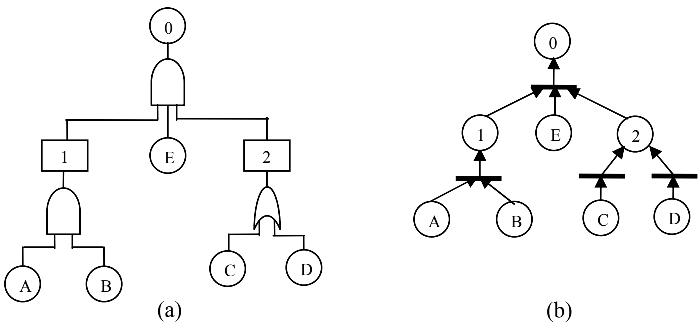

Fig. 2. **(a)** The fault tree model **(b)** The Petri net transformation

VAGUE SET THEORY

In this section some basic definitions related to vague sets and arithmetic operations between triangular vague sets are presented.

Basic definitions

Definition 3.1 (Gau & Buehrer, 1993) A vague set $\tilde{V} = \{x, \mu_{\tilde{V}}(x), 1 - \nu_{\tilde{V}}(x) \mid x \in X\}$ on the universal set X is characterized by a truth membership function $\mu_{\tilde{V}}$, $\mu_{\tilde{V}} : X \to [0,1]$ and a false membership function $\nu_{\tilde{V}}$, $\nu_{\tilde{V}} : X \to [0,1]$. The values $\mu_{\tilde{V}}(x)$ and $\nu_{\tilde{V}}(x)$ represents the degree of truth membership and degree of false membership of x and always satisfies the condition $\mu_{\tilde{V}}(x) + \nu_{\tilde{V}}(x) \leq 1 \;\; \forall \;\; x \in X$. The value $1 - \mu_{\tilde{V}}(x) - \nu_{\tilde{V}}(x)$ represents the degree of hesitation of $x \in X$.

For example, if the membership values of a vague set $\tilde{V}$ on the universal set X is $[0.5, 0.7]$, then $\mu_{\tilde{V}}(X) = 0.5$, $1 - \nu_{\tilde{V}}(X) = 0.7$ and $\nu_{\tilde{V}}(X) = 0.3$. This means that X belong to vague set $\tilde{V}$ with accept evidence is 0.5, decline evidence is 0.3. If X is the vote result from ten people, it implies that five people vote in favor, three persons vote against, and two persons is abstention. The uncertainty of X can be described by differential value of $1 - \nu_{\tilde{V}}(X) - \mu_{\tilde{V}}(X)$. If the differential value is small, then the value of X is more certain and if the differential value is high, then the value of X is more uncertain. The crisp sets and fuzzy sets are the special cases of vague sets. If $1 - \nu_{\tilde{V}}(X) = \mu_{\tilde{V}}(X)$, then vague set $\tilde{V}$ regresses to a fuzzy set. And if $1 - \nu_{\tilde{V}}(X) = \mu_{\tilde{V}}(X) = 1$ or $1 - \nu_{\tilde{V}}(X) = \mu_{\tilde{V}}(X) = 0$, then vague set $\tilde{V}$ regresses to a crisp set. Therefore, vague sets can be used to describe real life in more intelligent manner than crisp and fuzzy sets.

Definition 3.2 (Gau & Buehrer, 1993) A vague set $\tilde{V} = \langle [(a,b,c); \mu, \nu] \rangle$ is said to be a triangular vague set if its membership function is given by:

$$\mu_{\tilde{V}}(x) = \begin{cases} \mu\left(\dfrac{x-a}{b-a}\right), & a \leq x < b \\ \mu & , \; x = b \\ \mu\left(\dfrac{c-x}{c-b}\right) & , \; b < x \leq c \\ 0 & , \; otherwise \end{cases} \quad and \quad 1 - \nu_{\tilde{V}}(x) = \begin{cases} \nu\left(\dfrac{x-a}{b-a}\right), & a \leq x < b \\ \nu & , \; x = b \\ \nu\left(\dfrac{c-x}{c-b}\right), & b < x \leq c \\ 0 & , \; otherwise \end{cases}$$

Definition 3.3 (Chang & Cheng, 2009) Let $\tilde{V}$ be a vague set of the universe of discourse X with α-cut $\tilde{V}_\alpha = [a, b]$, where

$$a = \{x{:}\mu_{\tilde{V}}(x) \geq \alpha, x \in X\} \;\; and \;\; b = \{x{:}\; 1 - \nu_{\tilde{V}}(x) \geq \alpha, x \in X\}, \alpha \in [0,1] \quad (1)$$

Definition 3.4 (Chang & Cheng, 2009) Let $A_\alpha = [a, b]$and $B_\alpha = [d, e]$ be the α-cut of vague set. Then

$$(i) \quad [a, b] + [d, e] = [a + d, b + e] \tag{2}$$

$$(ii) \quad [a, b] - [d, e] = [a - e, b - d] \tag{3}$$

$$(iii) \quad [a, b] \times [d, e] = [\min(ad, ae, bd, be), \quad \max(ad, ae, bd, be)] \tag{4}$$

$$(iv) \quad \frac{[a, b]}{[d, e]} = \left[\min\left(\frac{a}{d}, \frac{a}{e}, \frac{b}{d}, \frac{b}{e}\right), \quad \max\left(\frac{a}{d}, \frac{a}{e}, \frac{b}{d}, \frac{b}{e}\right)\right] \tag{5}$$

In interval division, in order to avoid 0, we must limit $0 \notin [d, e]$.

Table 1. Conventional expression for the lambda-tau method

Gate	λ_{AND}	τ_{AND}	λ_{OR}	τ_{OR}
Conventional expression (n-Inputs)	$\prod_{j}^{n} \lambda_j \left[\sum_{i=1}^{n} \prod_{\substack{j=1 \\ 1 \neq j}}^{n} \tau_j\right]$	$\dfrac{\prod_{i=1}^{n} \tau_j}{\sum_{j=1}^{n} \left[\prod_{\substack{i=1 \\ i \neq j}}^{n} \tau_i\right]}$	$\sum_{j=1}^{n} \lambda_j$	$\dfrac{\sum_{j=1}^{n} \lambda_j \tau_j}{\sum_{j=1}^{n} \lambda_j}$

Table 2. Reliability parameters for repairable system

Parameters	Expression
Mean time to failure (h)	$MTTF_s = \dfrac{1}{\lambda_s}$
Mean time to repair (h)	$MTTR_s = \dfrac{1}{\mu_s} = \tau_s$
Mean time between failure (h)	$MTBF_s = MTTF_s + MTTR_s$
Availability	$A_s(t) = \dfrac{\mu_s}{\lambda_s + \mu_s} + \dfrac{\lambda_s}{\lambda_s + \mu_s} e^{-(\lambda_s + \mu_s)t}$
Reliability	$R_s(t) = e^{-\lambda_s t}$
Expected number of failures	$W_S(0, t) = \dfrac{\lambda_S \mu_S}{\lambda_S + \mu_S} t + \dfrac{\lambda_S^2}{(\lambda_S + \mu_S)^2} [1 - e^{-(\lambda_S + \mu_S)t}]$

PROPOSED VAGUE LAMBDA-TAU METHODOLOGY FOR RELIABILITY ANALYSIS

Sharma *et al*. (2008) adopted fuzzy lambda-tau methodology for evaluating the reliability indices of industrial system. The fuzzy lambda-tau methodology is generally used when the data is incomplete or the failure probability is extremely small. In fuzzy lambda-tau methodology the highest level of confidence of domain experts is assumed as 1. In real life problems the highest level of confidence of domain experts lies between $[0, 1]$ according to the expert's knowledge. To overcome the above-mentioned shortcoming, vague lambda-tau methodology for reliability analysis of a system is proposed. In this method, the constant rates are taken because most of the electrical system exhibits constant failure and repair rates and it is the most commonly distribution used in reliability engineering. In terms of implementing arithmetic operations of vague set in reliability analysis, the conventional lambda-tau expressions given in Table 1 and Table 2 are modified, using Equation 1-5 and α-cuts for the vague sets, which is stated as follows:

Let the failure rate and repair rate be represented by triangular vague set $\tilde{\lambda}_i = \langle [(\lambda_{i1}, \lambda_{i2}, \lambda_{i3}); \mu_i, \nu_i] \rangle$ and $\tilde{\tau}_i = \langle [(\tau_{i1}, \tau_{i2}, \tau_{i3}); \mu_i, \nu_i] \rangle$. The α-cuts for the vague sets $(\tilde{\lambda})$ and $(\tilde{\tau})$ are given as:

For "OR" transition

$$\begin{aligned} \lambda_i(\alpha_\mu) &= \left[\sum_{i=1}^{n} \left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\mu}{\mu_i} + \lambda_{i1} \right\}, \sum_{i=1}^{n} \left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\mu}{\mu_i} + \lambda_{i3} \right\} \right], \\ \lambda_i(\alpha_{1-\nu}) &= \left[\sum_{i=1}^{n} \left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i1} \right\}, \sum_{i=1}^{n} \left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i3} \right\} \right], \end{aligned} \tag{6}$$

$$\tau_i(\alpha_\mu) = \frac{\sum_{i=1}^{n} \left[\left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\mu}{\mu_1} + \lambda_{i1} \right\} \left\{ (\tau_{i2} - \tau_{i1}) \frac{\alpha_\mu}{\mu_i} + \tau_{i1} \right\} \right]}{\sum_{i=1}^{n} \left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\mu}{\mu_i} + \lambda_{i3} \right\}}, \frac{\sum_{i=1}^{n} \left[\left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\mu}{\mu_i} + \lambda_{i3} \right\} \left\{ -(\tau_{i3} - \tau_{i2}) \frac{\alpha_\mu}{\mu_i} + \tau_{i3} \right\} \right]}{\sum_{i=1}^{n} \left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\mu}{\mu_i} + \lambda_{i1} \right\}},$$

$$\tau_i(\alpha_{1-\nu}) = \frac{\sum_{i=1}^{n} \left[\left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i1} \right\} \left\{ (\tau_{i2} - \tau_{i1}) \frac{\alpha_\nu}{\nu_i} + \tau_{i1} \right\} \right]}{\sum_{i=1}^{n} \left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i3} \right\}}, \frac{\sum_{i=1}^{n} \left[\left\{ -(\lambda_{i3} - \lambda_{i2}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i3} \right\} \left\{ -(\tau_{i3} - \tau_{i2}) \frac{\alpha_\nu}{\nu} + \tau_{i3} \right\} \right]}{\sum_{i=1}^{n} \left\{ (\lambda_{i2} - \lambda_{i1}) \frac{\alpha_\nu}{\nu_i} + \lambda_{i1} \right\}}, \tag{7}$$

For "AND" transition

$$\lambda_i(\alpha_\mu) = \left[\prod_{i=1}^{n}\left\{\left((\lambda_{i2}-\lambda_{i1})\frac{\alpha_\mu}{\mu_i}+\lambda_{i1}\right)\right\}.\sum_{j=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\mu}{\mu_i}+\tau_{i1}\right\}\right],\right.$$
$$\left.\prod_{i=1}^{n}\left\{-(\lambda_{i3}-\lambda_{i2})\frac{\alpha_\mu}{\mu_i}+\lambda_{i3}\right\}.\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\mu}{\mu_i}+\tau_{i3}\right\}\right]\right].$$

$$\lambda_i(\alpha_{1-\nu}) = \left[\prod_{i=1}^{n}\left\{\left((\lambda_{i2}-\lambda_{i1})\frac{\alpha_\nu}{\nu_i}+\lambda_{i1}\right)\right\}.\sum_{j=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\nu}{\nu_i}+\tau_{i1}\right\}\right],\right.$$
$$\left.\prod_{i=1}^{n}\left\{-(\lambda_{i3}-\lambda_{i2})\frac{\alpha_\nu}{\nu_i}+\lambda_{i3}\right\}.\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\nu}{\nu_i}+\tau_{i3}\right\}\right]\right]. \tag{8}$$

$$\tau_i(\alpha_\mu) = \frac{\prod_{i=1}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\mu}{\mu_i}+\tau_{i1}\right\}}{\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}^{n}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\mu}{\mu_i}+\tau_{i3}\right\}\right]}, \frac{\prod_{i=1}^{n}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\mu}{\mu_i}+\tau_{i3}\right\}}{\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\i\neq j}}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\mu}{\mu_i}+\tau_{i1}\right\}\right]},$$
$$\tau_i(\alpha_{1-\nu}) = \frac{\prod_{i=1}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\nu}{\nu_i}+\tau_{i1}\right\}}{\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\1\neq j}}^{n}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\nu}{\nu_i}+\tau_{i3}\right\}\right]}, \frac{\prod_{i=1}^{n}\left\{-(\tau_{i3}-\tau_{i2})\frac{\alpha_\nu}{\nu_i}+\tau_{i3}\right\}}{\sum_{i=1}^{n}\left[\prod_{\substack{i=j\\1\neq j}}^{n}\left\{(\tau_{i2}-\tau_{i1})\frac{\alpha_\nu}{\nu_i}+\tau_{i1}\right\}\right]}. \tag{9}$$

where, $\forall\alpha_\mu \in [0,\mu]$ and $\forall\alpha_\nu \in [0,\nu]$.

In order to implement the proposed method for reliability analysis of the repairable systems, first construct the fault tree model of the repairable systems according to its sub-components failure reasons. Then, obtained the Petri net model from its equivalent fault tree model and using the matrix method (Liu & Chiou, 1997) calculate its minimal cut sets. Using the Equations 6-9 and minimal cut sets, calculate all quantified parameters such as the *expected number of failures* (ENOF), *mean time between failures* (MTBF), *availability* ($\tilde{A}_T$),and *reliability* ($\tilde{R}_T$) at different levels of α-cuts.

AN ILLUSTRATION

An illustrative example of a 66/11 KV substation in Patiala, India is presented in order to demonstrate the technique that is presented in this paper. The first step is to construct the fault tree of a substation that allows the definition of the functional/logical links between the equipment subsystems. Although all substations possess essentially the same subsystems, such as Buses, Breakers, Relay and Transformers, still there are differences between the topologies used in the station; therefore the fault tree must be developed for each specific topology used in substation. As shown in Figure 3, this system having one power supply source i.e. from PSEB (Punjab state electricity board), this source supply power to two systems (1 and 2). Each of them has a transformers T/F 1 and T/F 2; the primary breakers, CB1 and CB2; secondary breakers, CB3 and CB4; and over-current protections. These systems (1 and 2) are further connected with two feeders (I1and I2).

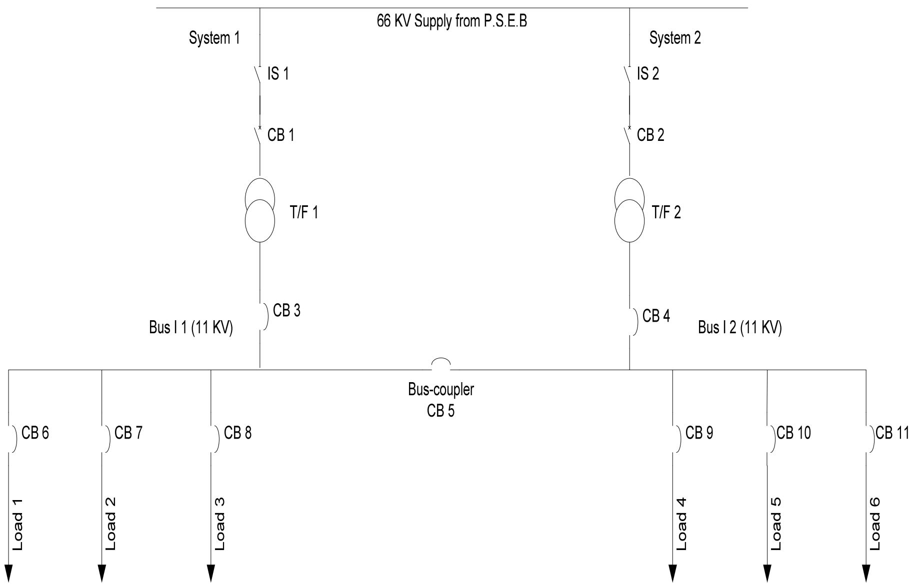

Fig. 3. A single line diagram of 66/11 kV substation

The two feeder systems are inter-connected by the bus-coupler CB5. This bus-coupler is normally closed and open only to isolate both systems (I1 and I2). This system has six loads (L1 to L6); L1 to L3 are connected to feeder I1 and L4 to L6 are connected to feeder I2, each of which equipped with a breaker system. The fault tree of a substation is shown in Figure 3. The failure of the system is when all of L1-L6 loads are outage. The TOP event of the fault tree is "All Loads L1 to L6 power loss". The probability of failures of breakers is very small which could be neglected. The bus-coupler CB5 only can cause the outage of the total system. If fault on one incomer I1, the failure of the bus-coupler CB5 cause the loss of both incomer I1 and I2 means power loss of all loads. Other failure events that will cause the system failure are the power loss of both transformer systems. These failures might be the failure in the bus, or the fault of transformer, or the power loss from the power supply source.

The fault tree of a substation is shown in Figure 4 and its Petri nets model is shown in Figure 5.

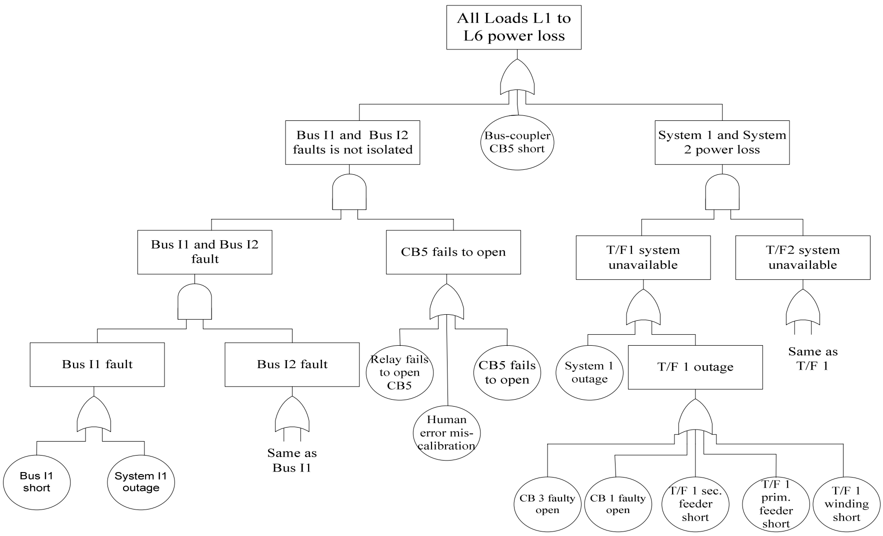

Fig. 4. Fault tree model of 66/11 KV substation

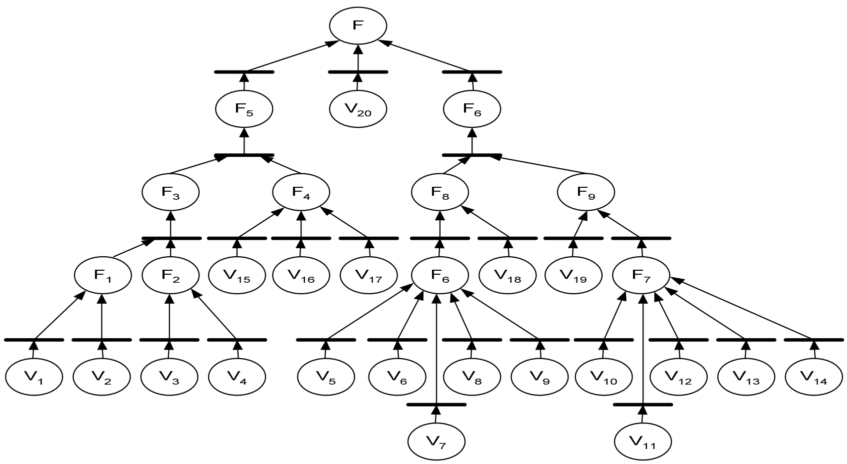

Fig. 5. Petri net model of 66/11 KV substation

Table 3. The possible ranges of failure rate $\left(h^{-1}\right)$and repair time (h).

$\lambda_{V_1} = 0.003, \lambda_{V_2} = 0.005, \lambda_{V_3} = 0.0013, \lambda_{V_4} = \lambda_{V_3}, \lambda_{V_5} = 0.0051, \lambda_{V_6} = 0.0015, \lambda_{V_7} = \lambda_{V_1},$
$\lambda_{V_8} = \lambda_{V_3}, \lambda_{V_9} = \lambda_{V_3}, \lambda_{V_{10}} = \lambda_{V_6}, \lambda_{V_{11}} = 0.002, \lambda_{V_{12}} = 0.007, \lambda_{V_{13}} = \lambda_{V_1}, \lambda_{V_{14}} = 0.001,$
$\lambda_{V_{15}} = \lambda_{V_3}, \lambda_{V_{16}} = \lambda_{V_6}, \lambda_{V_{17}} = \lambda_{V_{11}}, \lambda_{V_{18}} = \lambda_{V_{14}}, \lambda_{V_{19}} = \lambda_{V_1}, \lambda_{V_{20}} = \lambda_{V_{14}}.$
$\tau_{V_1} = 10, \tau_{V_2} = 10, \tau_{V_3} = \quad 2, \tau_{V_4} = \tau_{V_3}, \tau_{V_5} = \quad 3, \tau_{V_7} = \quad 4, \tau_{V_8} = 10, \tau_{V_8} = \tau_{V_1}, \tau_{V_9} = \tau_{V_3}, \tau_{V_{10}} = 3, \tau_{V_{11}}$
$= 4, \tau_{V_{11}} = 10, \tau_{V_{13}} = \tau_{V_1}, \tau_{V_{14}} = 2, \tau_{V_{15}} = \tau_{V_3}, \tau_{V_{16}} = 3, \tau_{V_{17}} = 4, \tau_{V_{18}} = 10, \tau_{V_{19}} = \tau_{V_1}, \tau_{V_{20}} = 2.$

Vague reliability assessment of 66/11 KV substation

The steps for evaluating the vague reliability of the 66/11 KV substation are given below:

Step 1: To handle the uncertainties and imprecision in the reliability data, the crisp value of (λ) and (τ) given in the Table 3 with mission time $(t) =$ 1 month are converted into triangular vague sets with $\pm 15\%$ spread of the crisp value. The $(\tilde{\lambda})$ and $(\tilde{\tau})$ values, are represented by triangular vague sets, are shown in the Figure 6.

Step 2: After representing the vague probabilities of all the components of the Petri net model by triangular vague set, obtain the $(\tilde{\lambda})$ and $(\tilde{\tau})$ values of the system using the extension principle coupled with an α-cut and arithmetic operations of triangular vague set on conventional lambda-tau methodology as given in Equation 6-9.

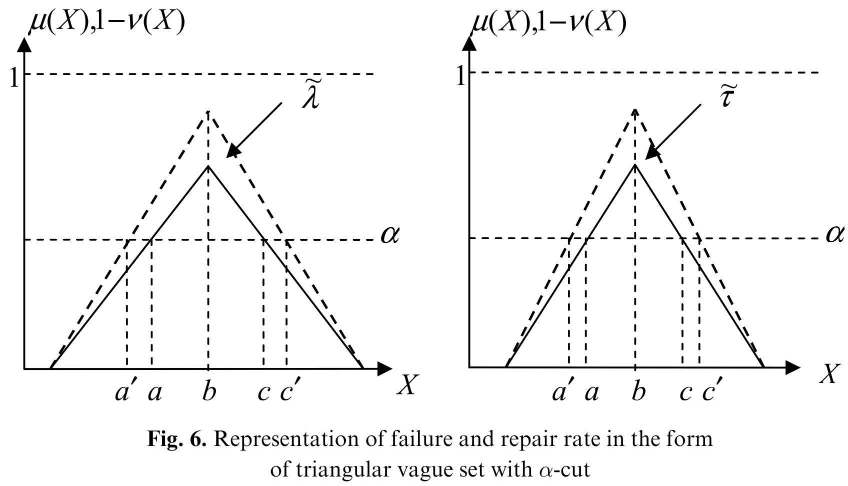

Fig. 6. Representation of failure and repair rate in the form of triangular vague set with α-cut

Step 3: After calculating the $(\tilde{\lambda})$ and $(\tilde{\tau})$ values of the top event of the system, they can be used in determining a number of quantifiable parameters such as the *expected number of failures* (ENOF), *mean time between failures* (MTBF), *availability* $(\tilde{A}_T)$,and *reliability* $(\tilde{R}_T)$ at different levels of α-cuts. The calculated values of vague reliability parameters for each α- level, is presented in Table 4 and Table 5 and plotted in Figure 7.

Table 4. Truth interval of confidence of the reliability parameter

	Left spread value						Right spread values					
α	λ $\times 10^{-2}$ (h^{-1})	τ (h)	R_T	A_T	ENOF $\times 10^{-2}$	MTBF $\times 10^{-3}$ (h)	λ $\times 10^{-2}$ (h^{-1})	τ (h)	R_T	A_T	ENOF $\times 10^{-2}$	MTBF $\times 10^{-3}$ (h)
0	0.096	1.1470	0.99856	0.99872	0.096	0.696	0.143	4.0326	0.99903	0.99935	0.143	1.0391
0.1	0.100	1.2711	0.99860	0.99878	0.100	0.718	0.139	3.6139	0.99899	0.99930	0.139	1.0019
0.2	0.103	1.4084	0.99864	0.99883	0.103	0.741	0.135	3.2432	0.99896	0.99925	0.135	0.9667
0.3	0.107	1.5605	0.99869	0.99889	0.107	0.764	0.130	2.9141	0.99892	0.99920	0.130	0.9334
0.4	0.111	1.7294	0.99873	0.99894	0.111	0.789	0.126	2.6213	0.99888	0.99915	0.126	0.9018
0.5	0.115	1.9172	0.99877	0.99899	0.114	0.815	0.1228	2.3600	0.99885	0.99910	0.122	0.8717
0.6	0.118	2.1265	0.99881	0.99905	0.118	0.843	0.118	2.1265	0.99881	0.99905	0.118	0.8431
0.7	--	--	--	--	--	--	--	--	--	--	--	--
0.8	--	--	--	--	--	--	--	--	--	--	--	--
0.9	--	--	--	--	--	--	--	--	--	--	--	--
1.0	--	--	--	--	--	--	--	--	--	--	--	--

Table 5. False interval of confidence of the reliability parameter

	Left spread value						Right spread values					
α	λ $\times 10^{-2}$ (h^{-1})	τ (h)	R_T	A_T	ENOF $\times 10^{-2}$	MTBF $\times 10^{-3}$ (h)	λ $\times 10^{-2}$ (h^{-1})	τ (h)	R_T	A_T	ENOF $\times 10^{-2}$	MTBF $\times 10^{-3}$ (h)
0	0.096	1.147	0.99856	0.99872	0.096	0.696	0.143	4.032	0.99903	0.99872	0.143	1.039
0.1	0.099	1.238	0.99859	0.99876	0.099	0.712	0.140	3.713	0.99900	0.99876	0.140	1.011
0.2	0.101	1.338	0.99862	0.99881	0.101	0.729	0.137	3.423	0.99898	0.99881	0.137	0.984
0.3	0.104	1.444	0.99865	0.99885	0.104	0.747	0.134	3.157	0.99895	0.99885	0.134	0.958
0.4	0.107	1.560	0.99869	0.99889	0.107	0.764	0.130	2.914	0.99892	0.99889	0.130	0.933
0.5	0.110	1.685	0.99872	0.99893	0.110	0.783	0.127	2.691	0.99889	0.99893	0.127	0.909
0.6	0.113	1.820	0.99875	0.99897	0.113	0.802	0.124	2.486	0.99886	0.99897	0.124	0.886
0.7	0.115	1.967	0.99878	0.99901	0.115	0.822	0.121	2.299	0.99884	0.99901	0.121	0.864
0.8	0.118	2.126	0.99881	0.99905	0.118	0.843	0.118	2.126	0.99881	0.99905	0.118	0.843
0.9	--	--	--	--	--	--	--	--	--	--	--	--
1.0	--	--	--	--	--	--	--	--	--	--	--	--

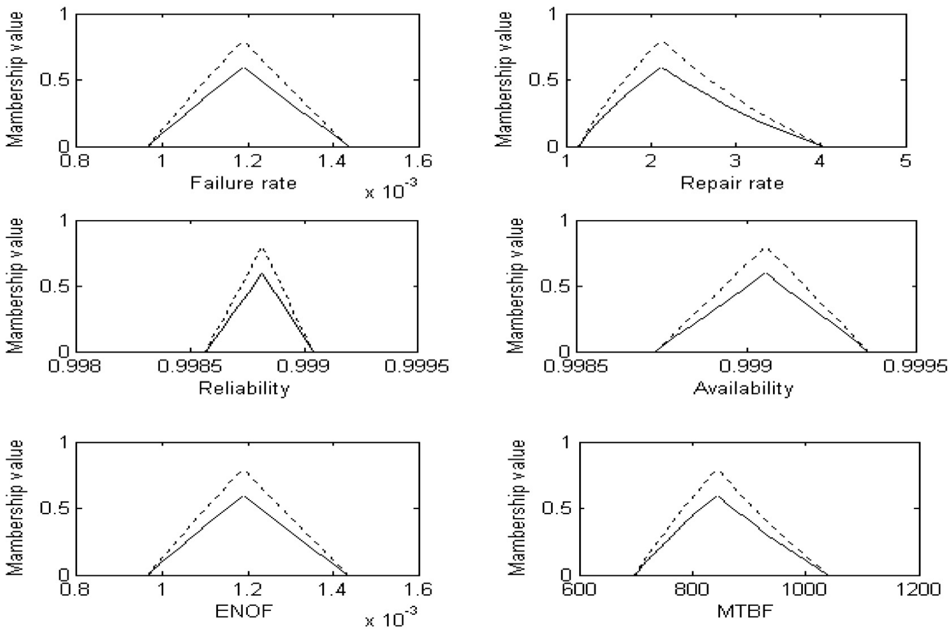

Fig. 7. Vague reliability parameters of the 66/11 KV substation

COMPARISONS AND DISCUSSION

The results obtained by using crisp reliability method, Sharma *et al.* (2008) and proposed method, for different membership values are shown in Table 6. The membership values, representing the vague reliability of a 66/11 KV substation, obtained by using the existing methods and proposed method are compared as follows:

(i) In crisp reliability (Liu & Chiou, 1997) method, the reliability of top event is equal to 0.99881 at all values of α, its means Liu & Chiou (1997) method does not consider any vagueness present in data. Liu & Chiou (1997) method is fit where the data are precise and certain, also it doesn't consider the confidence level of domain experts.

(ii) In Sharma *et al.* (2008) method, using Table 6, it can be seen that the degree of truth membership and false membership values correspond to reliability $r = 0.99873$ are 0.7 and 0.3 respectively. There is no degree of indeterminacy membership that the value of reliability is 0.99873. Also, Sharma *et al.* (2008) method does not consider the confidence level of domain experts (highest confidence, $\alpha = 1$).

(iii) In proposed method, using Table 6, it can be seen that the degree of truth membership and false membership values correspond to crisp reliability $r = 0.99873$ are 0.4 and 0.43 respectively. There is the 0.27 degree of indeterminacy membership that the value of reliability is 0.99873 which is not considered in both existing method. In the Sharma *et al.* (2008), analysis about the reliability of the system is presented by just one number, which presents the evidences both in favour and against the membership of any special value to be the reliability of the system. On the other hand, in proposed approach analysis is provided by two numbers representing the evidence in favour and the evidence against the membership of any especial value to be the reliability of the system. Also the proposed method considers confidence level of domain experts ($\alpha \leq 0.8$). Therefore, the proposed method can be more flexible.

Table 6. Comparison of the results obtained by using existing and proposed methods corresponding to different membership values

α	Crisp Reliability	Sharma *et al.* (2008)			Proposed approach				
		a	*b*	*c*	*a*	*a'*	*b*	*c'*	*c*
0	0.99881	0.99856	0.99881	0.99903	0.99856	0.99856	0.99881	0.99903	0.99903
0.1	0.99881	0.99858	0.99881	0.99900	0.99860	0.99859	0.99881	0.99900	0.99899
0.2	0.99881	0.99861	0.99881	0.99898	0.99864	0.99862	0.99881	0.99898	0.99896
0.3	0.99881	0.99863	0.99881	0.99896	0.99869	0.99865	0.99881	0.99895	0.99892
0.4	0.99881	.99866	0.99881	0.99894	0.99873	.99869	0.99881	0.99892	0.99888
0.5	0.99881	0.99868	0.99881	0.99892	0.99877	0.99872	0.99881	.99889	.99885
0.6	0.99881	0.99871	0.99881	0.99889	0.99881	0.99875	0.99881	0.99886	0.99881
.7	0.99881	0.99873	0.99881	0.99887	-	0.99878	0.99881	0.99884	--
0.8	0.99881	0.99876	0.99881	0.99885	--	0.99881	0.99881	0.99881	--
0.9	0.99881	0.99878	0.99881	0.99883	--	--	--	--	--
1.0	0.99881	0.99881	0.99881	0.99881	--	--	--	--	--

CONCLUSION

The main objective of this study was to develop a framework to model, analyze and predict the system behavior of the repairable systems. In this analysis, the Petri net model is obtained from its equivalent fault tree and in quantitative analysis, the reliability parameters (such as *expected number of failures*, mean time between failures, availability, and reliability) are evaluated using vague lambda-tau methodology. The proposed, vague sets based reliability analysis not only overcome the limitations associated with traditional approaches but also integrates the confidence level of domain experts and expert's experience, in more flexible and realistic manner.

Thus, it is concluded from the study that using proposed approach, the system reliability of the repairable systems can be analyzed in a more flexible and intelligent manner.

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تحليل الأداء للمحطة الفرعية 66/11 KV بإستخدام منهجية شبكات بتري وفاغ لامدا تاو

مانجت فيرما و أمت كومار

كلية تطبيقات الرياضيات والحاسوب – جامعة ثابار– باتيالا – الهند

خلاصة

نقترح في هذا البحث منهجية جديدة، مسماة فاغ لامدا تاو، لتحليل الوثوقية للأنظمة الممكن إصلاحها. وتعتمد هذة المنهجية على دمج نظرية المجموعات الغامضة بطريقة لامدا تاو المعروفة لتقييم العبارات الغامضة للانتقال أو / ولنموذج شبكات بتري. يدرس هذا البحث التحليل النوعي لنظام المحطة الفرعية 66/11 KV. في التحليل النوعي، نحصل على نموذج شبكة بتري من شجرة الخطأ المكافئة. أما في التحليل الكمي فنقوم بتقييم وسيطات الوثوقية بإستخدام منهجية فاغ لامدا تاو. ويمكن تحليل وثوقية النظام، باستخدام طريقتنا هذه، بشكل أكثر مرونة وأكثر ذكاءً.

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