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Substation Reliability Evaluation with Dependent Outages and Switching Failures Using Bayesian Networks

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ABSTRACT:
This paper presents an application of the Bayesian networks (BN) to substation reliability analysis. First part of the paper describes BN used to construct simple nodes, second shows the methodology used in constructing models of complex systems. A new model to represent dependent outages is introduced in the paper with a discussion how to avoid cycles when creating network models. This approach is then used to construct BN to model Switching Failures. A combination of path analysis with the Bayesian networks to enhance the construction of the latter is also presented.

Keywords: Reliability, Bayesian network, probability network, system reliability, dependent outages, switching failures

I. INTRODUCTION

There are many different methods for reliability analysis of electric power networks [15,3,6,4]. Reliability analysis based on Bayesian network belongs to a group of probabilistic methods. The term probabilistic network was first used in [14]. Since then, Bayesian networks (BN) are used for modeling knowledge in bioinformatics, medicine, biomonitoring, image processing, decision support systems [2] and engineering [17]. Probabilistic networks were also adapted for reliability analysis [1,10,7,11,13,12,5,8].

An important property of the Bayesian networks is clear and intuitively understandable graphical representation of the knowledge about the direct cause-effect relationships among the network elements. This allows for a more complete understanding of the modeled problem. Bayesian network inference takes place on the whole graph (takes into account the entire knowledge base), whereby it is possible to perform both causal inference (event - related causes) and effect relationships (event - related effects).

The advantages of the representation of cause-and-effect relationships using Bayesian networks include: the ability to easily extend and modify them in any direction of inference in which Bayes' rule can be used as well as to update the probability for a hypothesis as evidence is acquired [13]. Computer implementations of the Bayesian networks are limited compared to other solutions because it is a relatively new approach and requires preparation of probability tables to represent relationships between events.

The paper focuses on a combination of a path analysis with the Bayesian networks to enhance the construction of latter. Our goal is to calculate the reliability of electric power substations taking into account dependent outages of the selected components. It starts with an introduction to Bayesian networks in Section 2 followed by a discussion of simple networks in Section 3 and more complex ones in Section 4. The BN theory is then applied in Section 5 to the reliability analysis of some practical substation arrangements. Dependent Outages and Switching Failures and a methodology to construct BN are discussed in Sections 6 and 7. Construction of the BNs for five types of substation configurations together with numerical results, compared to Minimal Cuts Method are presented in Section 8. The last chapter contains the conclusions.

II. BAYESIAN NETWORKS

The probability of up-states $P(z_i) = p_i$ and down states $P(\overline{z}_i) = q_i$ of power system components can be expressed by the following formulas [9]:

$$P(z_i) = p_i = \frac{t_{ui}}{t_{ui} + t_{di}} = \frac{1}{1 + \lambda_i t_{di}} \quad (1)$$

where t_{ui} is the i^{th} element average up-state duration; t_{di} -average down-state duration, and λ_i represents failure intensity. We have:

$$P(z_i) + P(\bar{z}_i) = p_i + q_i = 1 \quad (2)$$

The probability of a system failure, depending on the state of its components, can be expressed in terms of conditional probability [2]:

$$P(z) = p_z = P(Z)P(z \mid Z_1, ..., Z_n) \quad (3)$$

$$P(\bar{z}) = q_z = P(Z)P(\bar{z} \mid Z_1, ..., Z_n) \quad (4)$$

where

$P(Z)$ is the joint probability being the sum of all combinations of unconditional probabilities of up and down-states of all elements, and

$P(z \mid Z_1, ..., Z_n)$ - the conditional probability of the power supply of the network node or lack thereof assigned to each of the possible combinations of unconditional probabilities given in the conditional probability table (CPT).

III. SIMPLE NETWORKS

We will start with two basic connections - series and parallel systems. For both of them, we can determine the cumulative probability of failure and success modes using simple Bayesian networks.

1.1. Series system (Fig.1, Fig.2, Table 1)

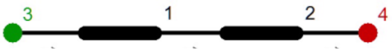


Fig. 1 Series system

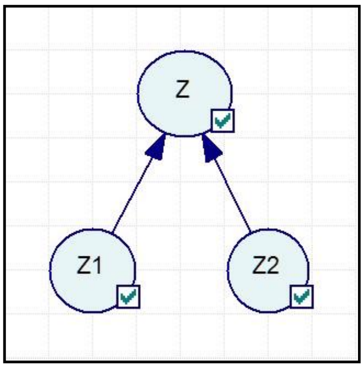


Fig. 2 BN for the series system

Table 1 CPT for the series system, i.e., node of AND type

Z_1	Z_2	$P(z \mid Z_1, Z_2)$	$P(\bar{z} \mid Z_1, Z_2)$
z_1	z_2	1	0
$\bar{z}_1$	z_2	0	1
z_1	$\bar{z}_2$	0	1
$\bar{z}_1$	$\bar{z}_2$	0	1

The total probability of a series system is given by:

$$P(Z) = p_1 p_2 + q_1 p_2 + p_1 q_2 + q_1 q_2 \quad (5)$$

Reliability is equal to:

$$P(z) = 1 \cdot p_1 p_2 + 0 \cdot q_1 p_2 + 0 \cdot p_1 q_2 + 0 \cdot q_1 q_2 \quad (6)$$

Probability of failure is given by:

$$P(\bar{z}) = 0 \cdot p_1 p_2 + 1 \cdot q_1 p_2 + 1 \cdot p_1 q_2 + 1 \cdot q_1 q_2 \quad (7)$$

1.2. Parallel system(Fig.3, Fig.4, Table 2)

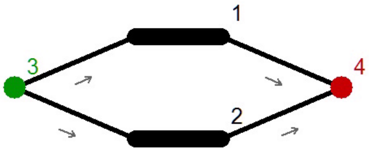


Fig. 3 Example of aarallel system

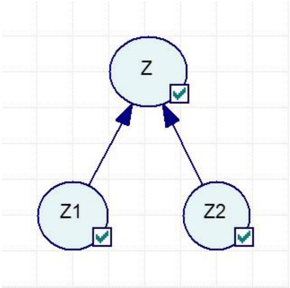


Fig. 4 BN for a parallel system

Table 2 CPT for the parallel system i.e., node of OR type

Z_1	Z_2	$P(z\|Z_1,Z_2)$	$P(\bar{z}\|Z_1,Z_2)$
z_1	z_2	1	0
$\bar{z}_1$	z_1	1	0
z_1	$\bar{z}_2$	1	0
$\bar{z}_1$	$\bar{z}_2$	0	1

The total probability is:

$$P(Z) = p_1 p_2 + q_1 p_2 + p_1 q_2 + q_1 q_2 \tag{8}$$

The probability of the system up state is given by:

$$P(z) = 1 \cdot p_1 p_2 + 1 \cdot q_1 p_2 + 1 \cdot p_1 q_2 + 0 \cdot q_1 q_2 \tag{9}$$

The probability of failure is given by:

$$P(\bar{z}) = 0 \cdot p_1 p_2 + 0 \cdot q_1 p_2 + 0 \cdot p_1 q_2 + 1 \cdot q_1 q_2 \tag{10}$$

IV. COMPLEX SYSTEMS

The analysis of complex systems is somewhat more involved. One of such systems can be the bridge-type arrangement of components (fragment of a breaker-and-half line termination in a substation shown in Fig. 5). The system works when the current is fed from any source (green nodes) to any sink (red nodes).

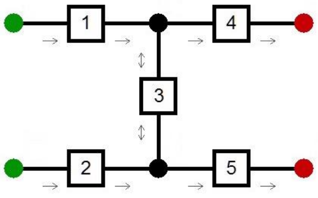


Fig. 5 Bridge system

We can create a Bayesian network for such a system in a number of ways. One of them (Fig 6.) is to create CPT for all possible combinations of states of the 5 elements. It is, however, laborious and very complicated since the size of the table increases exponentially with the number of elements. In the case of the 5 elements, we obtain $2^5 = 32$ states. The resultant table will consist of 32*2 =64 fields, and all of 32 states must be analyzed separately.

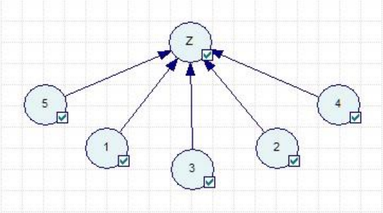


Fig. 6 Bridge system BN

The second way is to use the method of analysis of all paths and to add additional nodes to the Bayesian network (Fig. 7, Fig. 8). Each node is defined as a node of logical type AND or OR so that the CPT (Table 3, Table 4) of each node will be relatively small. For instance, node ‘or 1’ is an OR node for supplying power to the point '9' by the path through element '2' or the path through elements '1' and '3' (‘and 1’ is an additional node for the path).

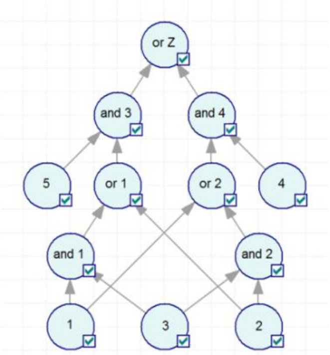


Fig. 7 BN for Bridge system

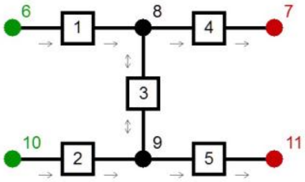


Fig. 8 Bridge system with added nodes 8 and 9

Table 3 CPT for the node ‘and 1’

Z_1	Z_3	$P(z_{\text{and1}}\|Z_1,Z_3)$	$P(\bar{z}_{\text{and1}}\|Z_1,Z_3)$
z_1	z_3	1	0
$\bar{z}_1$	z_3	0	1
z_1	$\bar{z}_3$	0	1
$\bar{z}_1$	$\bar{z}_3$	0	1

CPT's for nodes 'and 2', 'and 3' and 'and 4' are analogous

Table 4 CPT for the node 'or 1'

Z_1	Z_3	$P(z_{or1} \mid Z_{and1}, Z_2)$	$P(\overline{z}_{or1} \mid Z_{and1}, Z_2)$
Z_{and1}	z_3	1	0
$\overline{Z}_{and1}$	z_3	1	0
Z_{and1}	$\overline{z}_3$	1	0
$\overline{Z}_{and1}$	$\overline{z}_3$	0	1

CPT's for nodes 'or 2' and 'z' are analogous

It is clear that the definition of 7 simple tables with a total number of $7 \cdot (2 \cdot 2^2) = 56$ fields is much less complicated for this system. However, the process of creating layout for this network is complicated and not intuitive.

The third approach (Fig.9) is to look at all possible paths from a source to a sink and create an OR node for all of them. The result is a network with only 5 nodes, and 88 fields in total. This seems to be the best compromise – the process of finding all paths can be automated, and the resulting nodes are still quite small and what is even more important very simple (AND and OR nodes).

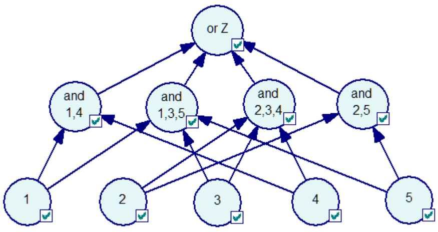


Fig. 9 BN for bridge system, all paths analysis

In case of more complicated systems, we can divide our BN model into multiple layers (Fig.10).

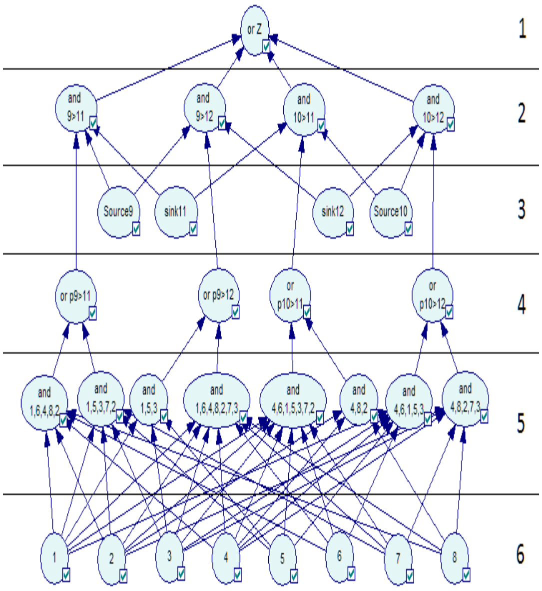


Fig. 10 Layers of BN example. Ring type substation configuration.

The following points describe the layers for this system.

1. Overall system failure probability is computed at node 'or Z'. We can define the node type based on our system up-state requirements. For example – OR node if we need only 1 out of n-sinks to be supplied.
2. Source to sink current transfer. Each node is in the up-state when both source and sink nodes are in the up-states and there is a connection (path) between them. AND type nodes.
3. Sources and sink layers. Each node is either a sink or source. Probability of failure of each must be predefined, based on the real world data.
4. Path availability layer. Node is in the up-state when at least one working path exists. OR type nodes.
5. Path layer. Each node represents a path between source and sink. All elements on the path must be in the up-state for the path to be available. AND type nodes.
6. Component layer. Each node is an element of the system. Probability of failure must be predefined.

V. SUBSTATION CONFIGURATION ANALYSIS

Nodes and the methodology of analysis of the paths presented in the earlier part of the work can be used for more complex systems representing the components of a substation.

We will consider five main substation configuration types:

- Single Bus
- Sectionalized Bus
- Ring Bus
- Breaker-and-a-Half
- Double Breaker-Double Bus

System configurations and corresponding Bayesian Networks are shown in Figs.11 – 15. Table 5 shows component reliability indices where λ is failure intensity and t_{di} is the average duration of the down-state. Using the formulas from Section II, failure probabilities $p(\overline{z})$ were calculated for each component. Those probabilities were then used as input values to the Bayesian Networks corresponding to each system layout.

Table 5 Component failure probabilities

Component	λ (1/y)	t_{di} (h)	$p(\overline{z})$
Line	0.002	15.48	3.53E-06
Transformer	0.002	15.48	3.53E-06
Breaker	0.024642	1010.77	2.84E-03
Bus	0.006	12.27	8.40E-06

For example, for the Ring Bus type substation, we start with layer ‘1’, node ‘or Z’. It is a node representing overall system failure probability. Then, in layer 2 we create 4 nodes for all possible connections between sources and sinks. The ‘or Z’ is an OR node, being in the up-state when any of the connected nodes: ‘and 9>11’, and 9>12’, ‘and 10>11’ and ‘and 10>12’ is in the up-state. Each of those nodes is in the up-state, when both corresponding source and sink nodes (layer 3) are in the up-states and there is a connection (path) between them. For node ‘and 9>11’, this node is in the up-state when both ‘Source 9’ and ‘Sink 11’ are in the up state and the node representing connection – ‘or p9>11’ is in the up state. Node ‘or p9>11’ is a path availability layer, it is an OR node, and it is in the up state when any of the paths beeteen Source9 and sink11 is available. There are 2 possible paths – one is through elements 1,6,4,8,2 and the second one is through elements 1,5,3,7,2. These paths are represented by nodes ‘and 1,6,4,8,2’ and ‘and 1,5,3,7,2’, respectively. Both nodes are AND type nodes, and they are in the up-state when all elements on the path are in the up-state. The last layer is a components layer. All component nodes have probabilities according to their element type given in Table 5.

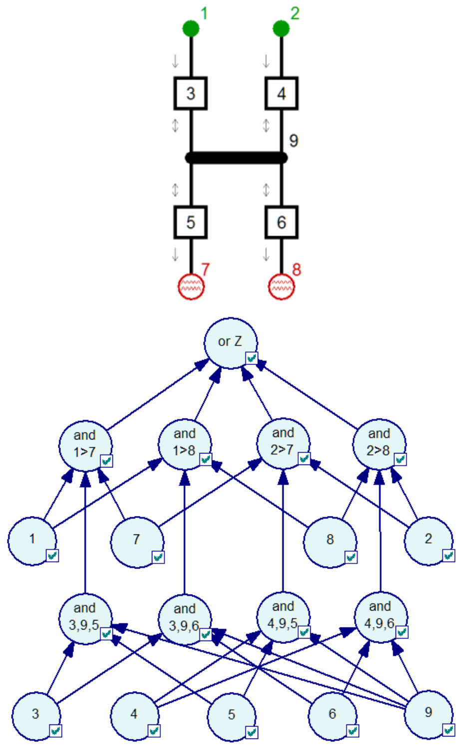


Fig. 11 Single bus substation configuration and BN

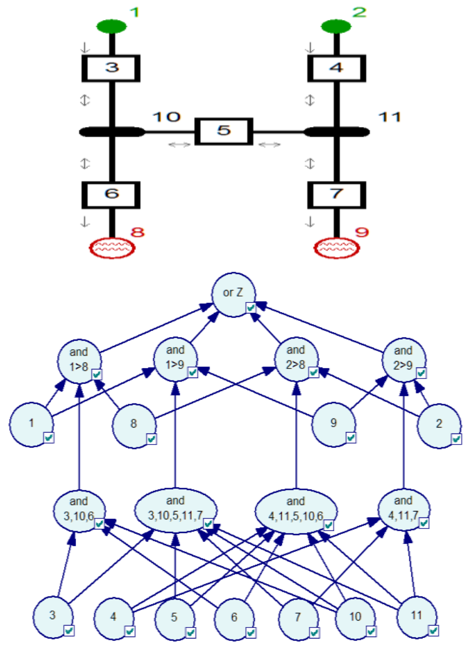
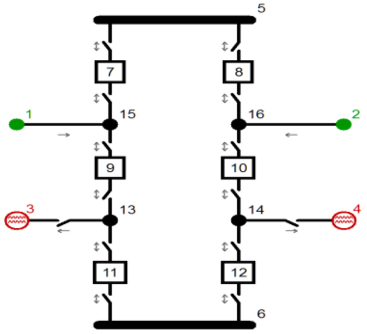


Fig. 12 Sectionalized type substation configuration and BN



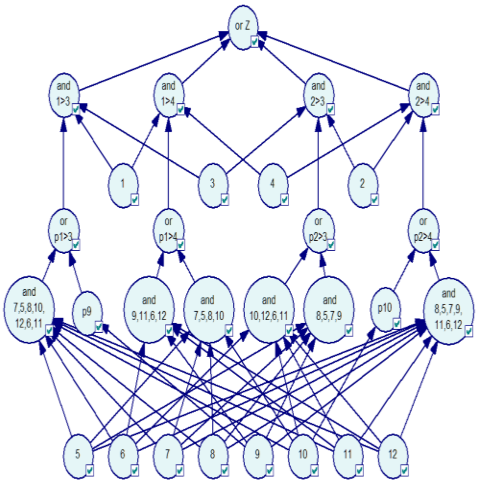
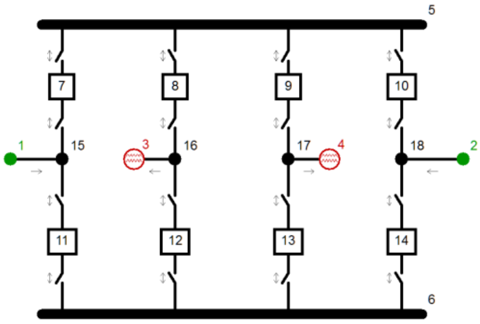


Fig. 13 Breaker-and-a-half substation configuration and BN



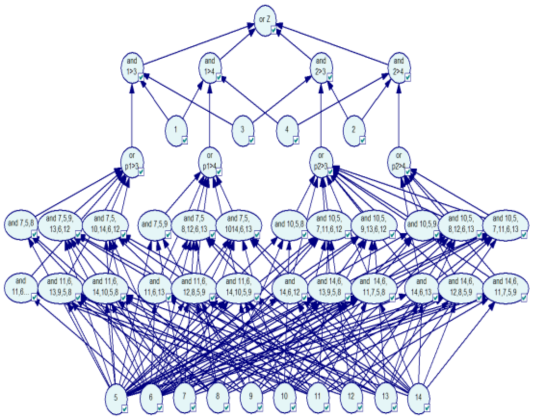
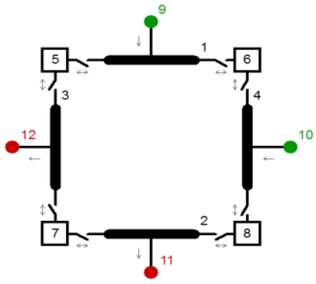


Fig. 14 Double Bus Double Breaker substation configuration and BN



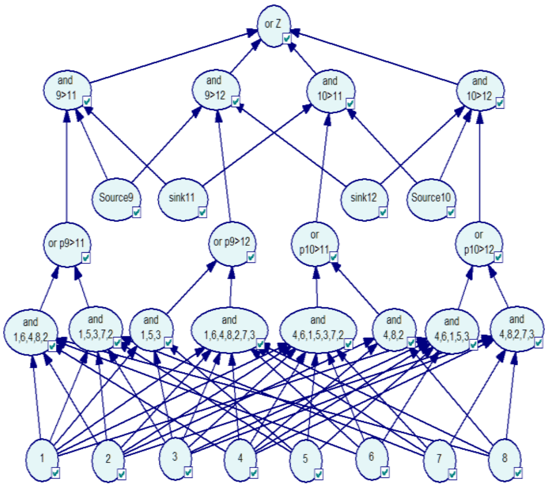


Fig. 15 Ring bus substation configuration and BN

Probabilities of failure for each system were also calculated using Minimal Cuts Method with the WinAREP program [9]. Results (shown in Table 6) are comparable. The small differences between probabilities obtained with the BN and AREP are due to the fact that AREP simply sums all probabilities, even if the events are dependent and BN takes that into account. The big difference in the Double Breaker – Double Bus is on the other hand caused by the fact that BN analyzed all possible failure states when AREP only of up to 3 simultaneous failures.

Table 6 Probabilities of failure of substation configurations

Layout	$p(\bar{Z})$ BN	$p(\bar{Z})$ AREP
Ring Bus	8.13E-06	8.17E-06
Double Breaker-Double Bus	9.79E-10	6.74E-10
Breaker-and-a-Half	8.04E-06	8.12E-06
Sectionalized Bus	1.63E-05	1.65E-05
Single Bus	2.45E-05	2.48E-05

VI. DEPENDENT OUTAGES

Dependencies can be modeled with the Bayesian Networks as follows. If a failure of element A can cause failure of element B, then we use simple arc from A to B. When failure of B can cause failure of A, we cannot add another arc because we would create a cycle. One way to avoid a cycle is to create additional nodes. For simple OR node (similar to Fig. 2.), the resulting conversion to a dependent OR node is presented below (Fig.16).

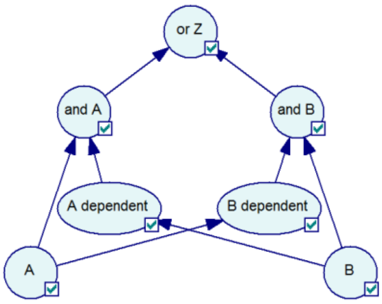


Fig. 16 BN for dependent failure event

The 'and A' node is of type AND and it is in the up-state when element A itself is in the up-state and when the node 'A dependent' is in the up-state. The node 'A dependent' is a node responsible for all dependent failures. The failure of element B can result with probability $q_{A|B}$ in failure of element A. The corresponding CPT for node 'A dependent' will have the following form (Table 7).

Table 7 CPT for the node 'A dependent'

Z_B	$P(z_{A\ dependent}\ \vert Z_B)$	$P(\bar{z}_{A\ dependent}\ \vert Z_B)$
z_B	1	0
$\bar{z}_B$	1- $q_{A\vert B}$	$q_{A\vert B}$

For example, let us consider Sectionalized System (Fig. 12) in which lines '1' and '2' are on a common tower. Let's assume that failure of one of the lines ('1' or '2') will result in a failure of the other one with probability 0.2. We can model such dependency with a BN shown in Fig. 17.

The resulting probability of failure for such system is 1.77E-05, slightly more than 1.63E-05 for this system without such dependencies.

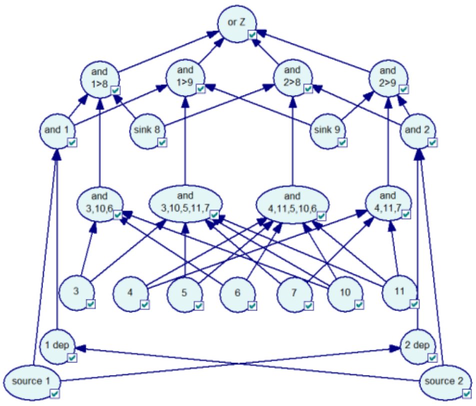


Fig. 17 BN for Sectionalized System with dependent line outages

VII. SWITCHING FAILURES

When a high-voltage device fails, first the system protection isolate a number of "healthy" components along with the one faulted; as soon as possible after that, all but the minimum number of components that must be kept out of service for the isolation of the failed device will be restored to operation through appropriate switching. Thus, while the component is in the failed state, the system moves through two states, those "before switching" and "after switching". Sometimes, when which is called Switching Failure. Although this type results in significantly shorter down-time, it may be more frequent type of failure.

A modification to proposed Bayesian Networks can be made to assess this type of failures. We can add additional layers of nodes (Fig.18.) to represent switching times for components, and switching breakers. First layer is the layer representing switching times of the components ('it' nodes: '9t', '11t', etc. colored in green). These nodes represent component nodes being in switching state when in failure state.

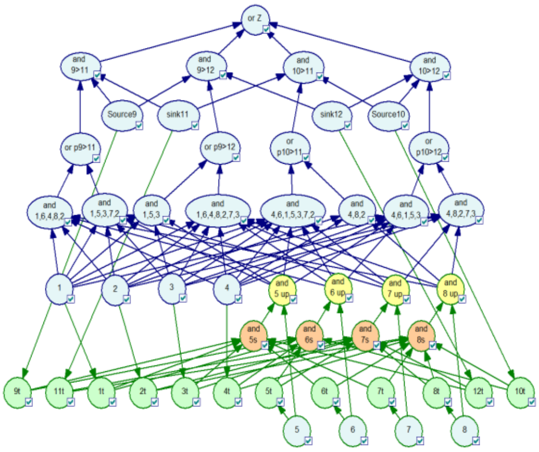


Fig. 18 Ring bus configuration with added switching layers

To calculate CPT for switching time nodes, we use the following formula:

$$P\left(\overline{z}_{s,i} \mid Z_i\right) = \frac{t_{s,i}}{\overline{t}_{a,i}} \qquad (11)$$

where $\overline{t}_{a,i}$ is the average down-time for the i-th element and $t_{s,i}$ is the average switching time for the i-th element. We can construct CPT for the switching time node (Table 8):

Table 8. CPT for switching node it

Z_i	$P(\overline{z}_{s,i} \mid Z_i)$	$P(z_{s,i} \mid Z_i)$
$\overline{z}_i$	$\frac{t_{s,i}}{\overline{t}_{a,i}}$	$1 - \frac{t_{s,i}}{\overline{t}_{a,i}}$
z_i	0	1

For example, for he node 'source9' the average down-state time is 15.48 hours and switching time is 0.4h. The probability of system being in a switching state for the element 'source9' when there is a failure in element 'source9' is equal to 0.4/15.48=0.0268. We can now construct CPT for the node '9t' (Table 9):

Table 9. CPT for node '9t'

Z_9	$P(\overline{z}_{s,9} \mid Z_9)$	$P(z_{s,9} \mid Z_9)$
$\overline{z}_9$	0.0268	0.9732
z_9	0	1

We can now construct nodes representing breakers switching states. These will be the AND type nodes. Each component has corresponding breaker zone – all breakers in that zone must open to isolate this component from the rest of the network. We connect each 'it' node with breakers surrounding the i-th component. For example, for element '5', the corresponding breaker zone consists of breakers '7' and '6', so we must connect node '5t' with node 'and 7s' and node 'and 6s'. We can construct CPT for switching node 'is' as follows (Table 10):

Table 10. CPT for node 'and is'

$Z_{k_1 s}$	…	$Z_{k_n s}$	$P(\overline{z}_{is} \mid Z_{k_1 s}, \dots, Z_{k_n}$	$P(z_{is} \mid Z_{k_1 s}, \dots, Z_{k}$
Every other combination			1	0
$z_{k_1 s}$	…	$z_{k_n s}$	0	1

Former breaker component nodes must now represent not only breaker failure but also switching (compare Fig.7. and Fig.8.). These are now AND type nodes – they are in up-state when corresponding breaker is in up-state and when that breaker is not open due to switching failure of any component for which that breaker is part of that elements breaker zone. These are 'iup' nodes: 'and 5up', 'and 6up' etc., colored yellow on the Fig.8. For example, node 'and 5up' is in up-state when both nodes: 'and 5s' and '5' are in up-state. The CPT for that type of nodes (Table 11):

Table 11. CPT for node 'and 5up'

Z_{5s}	Z_5	$P(\overline{z}_{5up} \mid Z_{5s}, Z_5)$	$P(z_{5up} \mid Z_{5s}, Z_5)$
$\overline{z}_{5s}$	z_5	1	0
z_{5s}	$\overline{z}_5$	1	0
$\overline{z}_{5s}$	$\overline{z}_5$	1	0
z_{5s}	z_5	0	1

VIII. BREAKER ANALYSIS RESULTS

Using methodology discussed in section 6 we can construct corresponding BN for the configurations presented in section 5. Values used to calculate corresponding probabilities are shown in Table 12:

Table 12. Component frequency, failure and switching times

Component	λ	$\bar{t}_{a,i}$	$t_{s,i}$
Line	0,002	15,48h	0,4h
Transformer	0,002	15,48h	0,4h
Breaker	0,024642	1010,77h	0,5h
Bus	0,006	12,27h	0,4h

Bayesian networks constructed and used for the analysis are shown below:

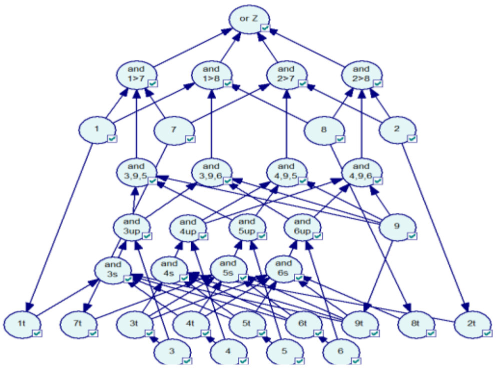


Fig. 19 BN for Single Bus configuration with added switching layers

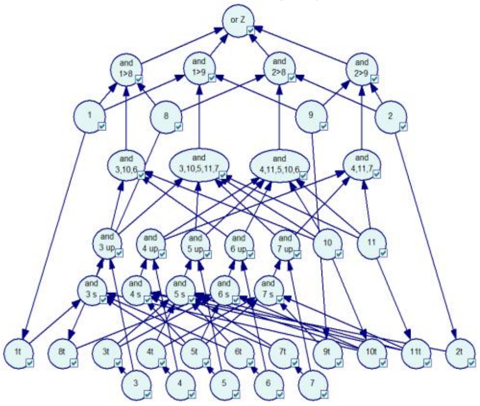


Fig. 20 BN for Sectionalized Bus configuration with added switching layers

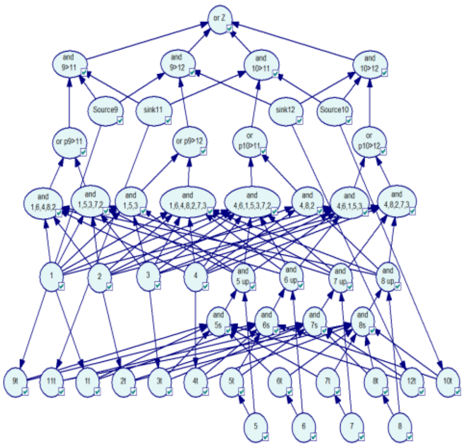


Fig. 21 BN for Ring Bus configuration with added switching layers

BN for Breaker-And-A-Half Bus configuration with added switching layers

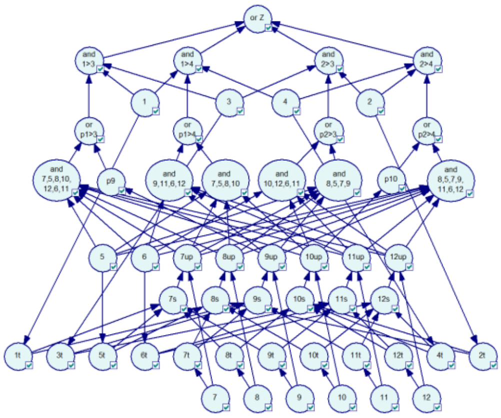


Fig. 22 BN for Breaker-And-A-Half Bus configuration with added switching layers

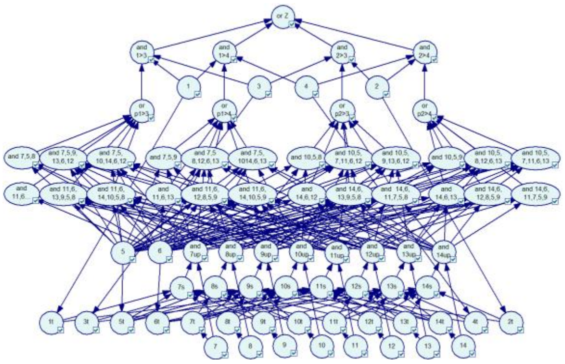


Fig. 23 BN for Double Bus Double Breaker configuration with added switching layers

Results obtained using BN models are comparable with results obtained using WinAREP software based on Minimal Cuts method. The small differences between probabilities obtained with BN and AREP are due to the fact that AREP simply sums all probabilities, even if they are dependent and BN takes that into account. Detailed results presents Table 13:

Table 13. Probablities of switching failure of substation configurations

Layout	$p(\bar{Z})$ BN Switching only	$p(\bar{Z})$ AREP Switching only
Ring Bus	2,46E-02	2,46E-02
Double Breaker-Double Bus	2,79E-04	2,82E-04
Breaker-and--a-Half	1,48E-04	1,50E-04
Sectionalized Bus	1,24E-02	1,25E-02
Single Bus	4,90E-02	4,93E-02

IX. CONCLUSIONS

Reliability analysis with Bayesian networks is a very powerful tool. Simple systems can be modeled by simple logic nodes from which complex systems can be created. Combination of the AND/OR nodes with possible path analysis is an effective way of modeling complex systems. Problem of defining large Conditional Probability Tables is avoided by using combination of simple nodes and adding additional nodes to the network. Results obtained with the BN are similar to the results obtained with the Minimum Cuts method, but more failure states can be analyzed. More than 3 elements being in a failure state simultaneously is a rare but possible situation and BNs are capable of analyzing all possible failure states. BN inference algorithms are usually NP-hard, which means that computational time increases exponentially with the number of nodes. On the other hand, Bayesian networks presented in this article, are constructed with relatively small and simple nodes, and do not require too much computational power. Constantly improving performance of modern computers should be enough to model efficiently most of the power system layouts.

Switching Failures can be modelled with the presented new approach. Creating cycles is avoided by adding extra nodes, representing dependent outages. Results obtained with BN are almost identical (BN are slightly more accurate) to the ones obtained with older Minimal Cuts Method.

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