Reliability Analysis of Breaker Arrangements in Distribution substations.

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ABSTRACT

Substations are the weakest link between the source of supply and the customer load points in a power system, because they comprise switching arrangements that would lead to loss of load. Determining the reliability expression of different substation configurations can help design a system with the best overall reliability. This paper presents a computerized and implemented method based on disjoint path-set method and its direct application on the evaluation of the reliability expression, reliability indices and costs of different switching arrangements.

Keywords:

Boolean function, pathsets, Power substation Reliability; RBD and reliability indices.

1. INTRODUCTION (HEAD 1)

In this paper the reliability of high voltage breaker arrangements is studied using a new Algorithm implemented in VC++ tool. Path set enumeration and Reliability Block Diagram analysis is used to perform reliability studies of different breaker arrangements. The different arrangements are assessed and compared. This paper introduces a modeling technique for analyzing breaker arrangements via Reliability Block Diagram.

The reliability performance of breaker arrangements is compared and discrepancies are explained.

This algorithm follows a sum of disjoint products (SDP) scheme, based on Boolean algebra and probability theory.

This paper is divided into four parts and proceeds as follows:

Part 1, deals with the algorithm implementation, along with its advantages and limitations.

In Part 2, the application of the software on various power substation configurations is illustrated. An example of simple radial distribution system is considered to clarify the profitability of this application in the study of power system reliability.

2. ALGORITHM.

The evaluation of network reliability, with two state components, is a common task in power distribution systems' reliability assessment. And with an increase in networks' size and complexity, the computation workload is assigned to computers. However, applying the previously discussed methods will result in a NP-hard problem.

State space approach: with n components, the event space consists of 2^n states. The probability of each of the states is to be computed.

Fault trees: requires the use of cut-set or tie-set, These sets are to be disjoint, according to the probability expression that is used for limited mutual independent events, resulting in 2^n-1 items.

$$P\left\{\bigcup_{r=1}^{n} M_r\right\} = \sum_{r=1}^{n} P\{M_r\} - \sum_{1\le r<s\le n} P\{M_r \cap M_s\} + \sum_{1\le r<s<t\le n} P\{M_r \cap M_s\} + \cdots + (-1)^{n-1} P\left\{\bigcap_{r=1}^{n} M_r\right\}$$

Where M_i s are the minimal sets.

Network approach: either use of network reduction method, which is impractical. Or path set method that will lead to same result as fault tree approach.

In order to overcome the previous difficulties, an algorithm for calculating system reliability by sum of disjoint products (SDP), based on Boolean algebra, is presented. This algorithm is applied to sum of minimal path sets.[1]

2.1 Sum of disjoint products algorithm:

The first step to decompose a sum of product is rather simple. The recursive method can be used for example.

Assume that M_1, M_2, M_3… M_n, are minimal path sets, and T is a sum of minimal path sets, Then, using recursive method:

$$T = \bigcup_{k=1}^{n} M_k = M_1 + \overline{M_1}M_2 + \overline{M_1M_2}M_3 + \ldots + \overline{M_1M_2} \ldots \overline{M_{n-1}}\, M_n \quad (9)$$

$$T = F_1 + F_2 + F_3 + \ldots + F_n \quad (10)$$

Where $F_r = C_r M_r$ and $C_r = \begin{cases} 1 & r = 1 \\ C_{r-1}\overline{M}_{r-1} & 1 < r \leq n \end{cases}$

Obviously, it has achieved disjoint products between items of formula (2), but each item is crossed. As a result, we decompose the complement set of each path set with De Morgan's law, and continue disjoint treatment. Since the number of basic event of the minimal path sets increases with the number of path sets, this method will quickly become overwhelming and impractical.

Four major disciplines for sum of disjoint products are given. If these disciplines are applicable then the steps to calculate the sum of products' probability will be considerably reduced.

2.2 Discipline for simplification:

The disciplines presented are based on Boolean algebra.

2.2.1 Distinction discipline

Supposing that minimal path sets M_1, M_2, M_3… M_k have not the same basic event, it is not essential to decompose the product item $\overline{M_1}\overline{M_2}$ … $\overline{M_{k-1}}M_k$ during quantitative calculation. If the probabilities are known as $P_{M_1}, P_{M_2}, P_{M_3}, P_{M_{k-1}} \dots P_{M_k}$ then

$$P(\overline{M_1}\overline{M_2} \dots \overline{M_{k-1}}M_k) = (1 - P_{M_1})(1 - P_{M_2})(1 - P_{M_3})\dots(1 - P_{M_{k-1}})P_{M_k} \quad (11)$$

Where $P_{M_k} = \prod p_{jk}$ p_{jk} stands for the probability of the event j in the path set k.

2.2.2 Elimination discipline

If the minimal path sets $M_1, M_2, M_3, \dots M_k$ have part event that are included in M_k, then these events can be eliminated from $M_1, M_2, M_3, \dots M_{k-1}$. New sets are formed $M_{1c}, M_{2c}, M_{3c}, \dots M_{(k-1)c}$ where

$$\overline{M_1}\,\overline{M_2} \dots \overline{M_{k-1}}M_k = \overline{M_{1c}}\,\overline{M_{2c}} \dots \overline{M_{(k-1)c}}M_k \qquad (12)$$

2.2.3 Absorption discipline

In the sets $M_{1c}, M_{2c}, M_{3c}, \dots M_{(k-1)c}$ that are dealt with elimination discipline, if the set M_{ic} has all the events of M_{jc} then M_{ic} is absorbed by M_{jc} so $\overline{M_{ic}}\,\overline{M_{jc}}M_k = \overline{M_{jc}}M_k$

2.2.4 Decomposition discipline

If $M_{1c}, M_{2c}, M_{3c}, \dots M_{(k-1)c}$, dealt with elimination discipline have a few same basic events, then we could use the formula below to decompose

$$\overline{M_{ic}}\,\overline{M_{jc}}M_k = \left(\overline{M_{ijc}} + M_{ijc}\overline{M_{icc}}\,\overline{M_{jcc}}\right)M_k \qquad (13)$$

Where M_{icc} and M_{jcc} stand for the products of basic events left except the same events of M_{ic} and M_{jc}.

2.3 Computer program implementation

2.3.1 . Implementation procedure

The first input to the program is the sum of minimal path sets. Therefore, the first thing to do is decomposing it into a sum of mutually exclusive products. This step is accomplished using the recursive method.

Since each of the resulting products is crossed, then it is disjoint separately, using the four disciplines aforementioned. First, the product is checked for distinction between the minimal path sets' basic events. If the entire minimal path sets (either complemented or not), forming this particular product, have independent events; therefore, the probability of this product can be computed straight forward. (Distinction discipline)

If the product is composed of dependent event then it is checked for repeated events in complemented path sets and the uncomplemented one. If any then it is discarded (Elimination discipline).

After the previous step, the complemented path sets of the product are checked for inclusion between them. If a minimal path set includes another one then it is absorbed by the latter (i.e. the first is discarded and the second is kept). (Absorption discipline)

If two complemented minimal path sets share basic events then the product is decomposed into a sum of two products. One sub-product is added to the list of products to be disjoint; the other sub-product (the one with the shared events only) is re-dealt with again (absorption and decomposition steps only). (Decomposition discipline)

The aforediscussed procedure is illustrated in the flow chart of figure2.

2.3.2 CPU and Memory Usage:

The implementation of this algorithm is based on a modular structure (i.e. using separate functions coded into black boxes). The same structure illustrated in the flow chart is used.

The order function of the initialization phase is $O(N,P) = P^2+NP$

Where P is the number of path sets and N is the number of variable.

For the product disjointing phase, the order function is $O(P) = P^{2P-2}$. This is basically due to the decomposition discipline. In case no decomposition is required then $O(P) = P^2$.

It is worth noticing that the order function of the product disjointing phase does not depend on the number of variable. This is due to the usage of bitwise property of C/C++.

Concerning memory usage, a linked list structure is used to store and manipulate the equations. Combined with dynamic memory allocation, this structure avoids unnecessary usage of memory. For this particular algorithm, the required memory is: P*(4+N) bytes for a max of variables of 8, P*(4+2N) bytes for a max of 16 and P*(4+4N) bytes for a max 32 variables. Plus enough space to hold input and output strings. The rest of the variables and buffers are local.

3. Application to Power Distribution Substations

Three of the previously described configurations are analyzed (Single bus, double breaker-double bus and ring bus). The components modeled are transformers, bus bars and breakers. These components are labeled in the following figures. For convenience, reclosers and source availability are assumed to be 100% reliable.

of current interest.

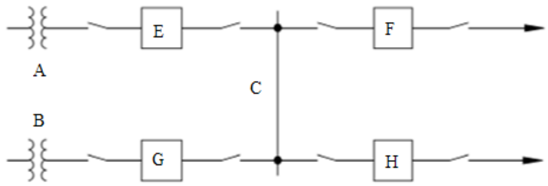

Figure3 Single bus with labeled components

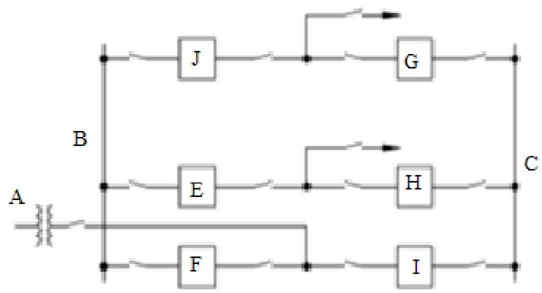

Figure 4: Double breaker-double bus labeled components

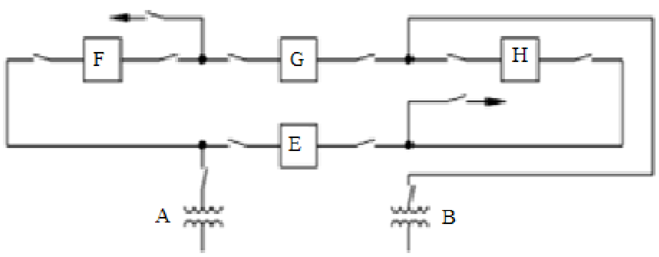

Figure 5: Ring bus labeled components.

It can be see that these configurations are symmetrical. Therefore, output nodes have equivalent path sets (i.e. the path sets have equal availabilities and transition rates). For each configuration, one output is considered, and their path sets are:
Single bus: AECF + BGCF
Double breaker-double bus: AFDE + AICH + AICHJDE + AFDJGCH
Ring bus: AF + AEHG + BG + BHEF
Where A and B are transformers, C and D are bus bars and E, F, G, H, I and J are breakers.
The component reliability data and cost for this example are taken as in Table 1. Revenue lost per hour of substation downtime is 22 000$. Average repair and start up cost per hour is 6000$, making it a total of 28000$.

Table 1: substation component reliability data. [8]table 7-15p129;table 7-1p105

Component	Failure rate λ (failure/year)	MTTR (hours)	Repair rate μ (repair/year)	Cost($)
Transformer	0.0030	342.0	25.61	48000
Bus bar	0.0017	24.0	365.0	500
Breaker	0.0036	83.1	105.4	12000

All of these data are inputted into the program and executed

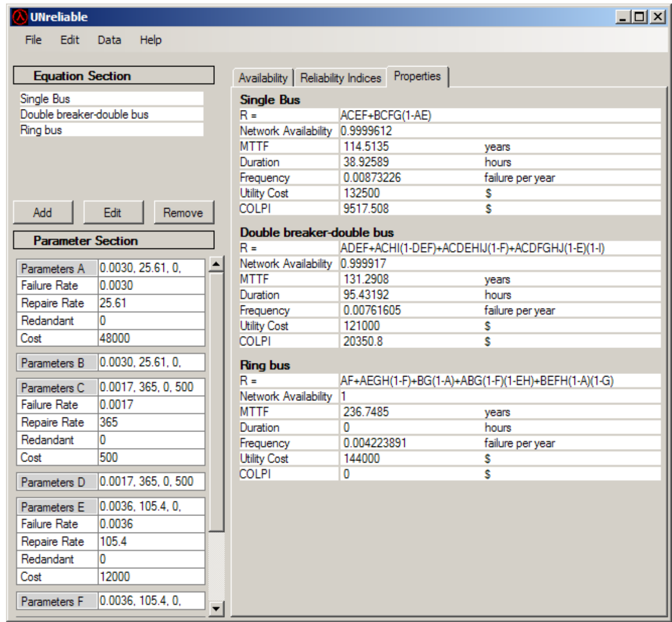

Figure 6: Reliability assessment results for single bus, double breaker-double bus and ring bus

3.1 . Comparison

The results are tabulated in Table 2. Even though reclosers are discarded (assumed reliable), their cost need to be considered. The total cost, then, is the summation of the utility cost (plus reclosers) and the cost of load point interruption COLPI (unserved power to costumer and repair cost).
For a 5000$ recloser, total cost has a plus of 8x5000$, 12x5000$ and 8x5000$ for single bus configuration, double breaker double bus and ring bus configuration, respectively.

Table 2: substation reliability indices.

Configuration	Availability	MTTF(y)	MTTR(h)	Frequency (fl/y)	Total Cost ($)
Single Bus	0.9999612	114.5	38.92	0.008732	182 017$
Double Breaker Double Bus	0.999917	131.3	95.43	0.007616	201 350$
Ring Bus	≈ 1	236.7	≈ 0	0.004223	184 000$

Even with its well-known low reliability, the single bus exhibits an excellent availability level (4 nines). This is due to the reliable components composing this substation (small failure rates and small repair times).
The double breaker double bus configuration has a slightly (but still 4 nines) lower availability than the single bus configuration. However, the mean time to failure MTTF as well as the failure frequency are less than that of the single bus configuration. The relatively high cost for this configuration disallows an unnecessary use of sophisticated configuration when made of reliable components.

The ring bus configuration's availability is 1 but still has a non-zero failure frequency. This is due to the rounding-off of the very high availability for this configuration. Also, this latter has a large mean time to failure and almost zero repair time in case of total failure.

3.2 Non-renewable (with and without spares) and Renewable Substations

An example of three system behaviors is illustrated, using a breaker and a half topology. This behaviors' investigation is very important in the design phase, especially when the system is made for a specific mission time. The components' parameters, for this example, are chosen for convenience, and are not based on any actual survey.
In this example only breakers are considered (all of the other components are assumed to be perfectly reliable). The network and labels are illustrated in Figure 7.

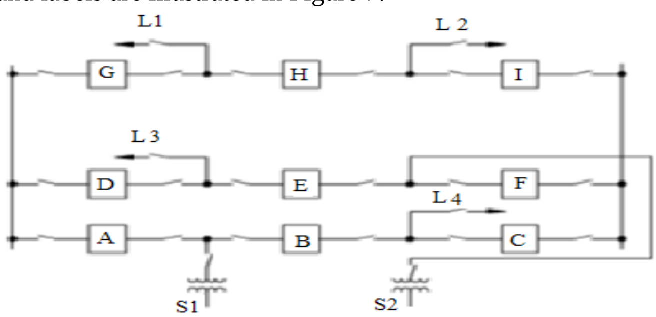

Figure 7: a breaker and a half substation configuration with labeled components
Path set for load point L1 is:
From S1: AG + BCIH + ADEFIH + BCFEDG
From S2: EDG + FIH + EDABCIH + FCBAG
The resulting minimal path set is: AG + EDG + FIH + BCIH
The reliability for non repairable components with spares is found using Poisons rule:[2-4]

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

Where n is the number of spares.
The reliability polynomial is used to compute the availability of this substation (since all of the components are identical and have the same reliability P) for the different cases considered here.

Availability | Reliability Indices | Properties

breaker and a half

R =	+P^2 +2P^3 -2P^5 -2P^6+P^7 +2P^8-P^9
Network Availability	
MTTF	years
Duration	hours
Frequency	failure per year
Utility Cost	$
COLPI	$

Figure 8: results of the disjoint algorithm on a breaker and a half

For the non-renewable mode, the breakers' failure rate is 0.36 failure/year. Then spares are used (4 spares). For the renewable case, the repair rate is considered to be 1 repair/year. For all of these cases, mission time is 40 years. A graph of the three cases is illustrated in Figure 9.

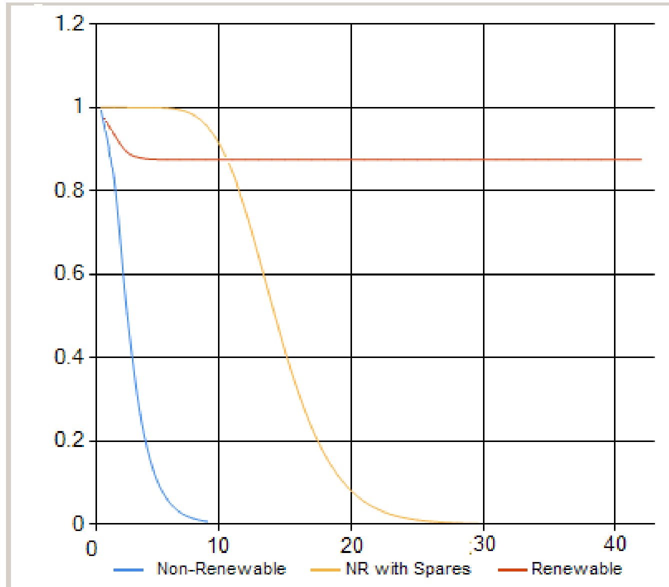

Figure 9: plot of a non-renewable (with and without spares) and a renewable behavior of breaker and a half substation

It is clear, from the graph that the renewable system has the highest availability. However, this is only true for a long run. For short mission systems, using spares provides higher reliability.

5. CONCLUSION

In this paper we investigated the reliability expression and indices of each substation configuration and on the use of the disjoint path algorithm because of it reduces the order of the execution time to 2^{2P-2} (P is the number of paths). While a direct approach or state space approach would result in an NP hard problem. Since this approach is based on Boolean algebra (and probability theory), multiple state systems are unpractical. Only two state components are considered.

Power distribution systems and, more specifically, power distribution substations are built from two state components. Therefore, the aforementioned algorithm is perfectly suited for power distribution system reliability assessment. The application of this algorithm not only saves computational effort but, because of the equivalence between electrical power networks and logic block diagrams, uses path set enumeration instead of the tedious state space enumeration. Moreover, path set enumeration algorithm can be used for that part.

Component's transition rates, when using this algorithm, need to be constant. Non-exponential components are not considered (dependent events). However, surveys on power distribution system components report constant transition rates during the component's normal operating time. This encourages the use of this algorithm. In the case where power load and available power are considered, the system becomes a composition of a multistate subsystem and two state subsystems. A combination (if applicable) of state space approach and the presented algorithm can solve the problem. As a future work, components with non-exponential distributions could be considered. Approximated models for these components and technique for approximation (such as Supplementary variable method) should be investigated. Other repair modes should be considered. Renewable components and the use of spares are not the only way to handle failure. Many widely used strategies need to be considered such as the use of standby units (cold or warm) or scheduled maintenance.

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