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A NOVEL ASSESSOR FOR DISTRIBUTION SYSTEM RELIABILITY

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الملخص

إن الاعتمادية هي موضوع رئيسيُ في تخطيط و تصميم نظم القوى. هذا البحثِ يُقدّمُ خوارزمية تحليلِ إعتمادية أنظمة توزيعِ كهربيةِ تعمل في شكل خطي بالنسبة لمحطات المحولات ولها القدرة على إعادة التشكيل. تَأْخذُ الخوارزميةُ في الحسبان عند برمجتها على الحاسب الآلي مُعَالَجَة قيود وحدات أجهزة القوى الكهربية. وفي الخوارزم المقترح تمثل المنظومة بقوائم لأجزاء من مكوناتها تسمى "القِطَع" تعمل على التّقاربِ السّريع للحل الأمثل عند تمثيل المنظومة على الحاسوب. ويستخدم حساب تدفق القوى لمراقبة ومعالجة قيود الخوارزم. وقد تم برمجة الخوارزمية على الحاسوب باستعمال برنامج MATLAB

ABSTRACT

Reliability is a key aspect of power system design and planning. This research presents a reliability analysis algorithm for radial operated (with respect to substation), reconfigurable, electrical distribution systems. The algorithm takes into account equipment power handling constraints. Linked lists of segments are employed in obtaining the rapid convergence. The study presented here evaluates improvement of reliability for static load models. A new reliability index is proposed. The proposed index makes easier to locate areas where reliability needs to be improved. Reliability indices for load points and the overall system have been developed.

INDEX TERMS: power system reliability, set, segment, circuit traces, linked list.

1 INTRODUCTION

The economic and social effects of loss of electric service have significant impacts on both the utility supplying electric energy and the end users of electric service. The power system is vulnerable [1] to system abnormalities, such as control failures, protection or communication system failures, and disturbances, such as lightning, and human operational errors. Therefore, maintaining a reliable power supply is a very important issue for power systems design and operation.

This paper presents the research efforts and the software implementation of a reliability analysis algorithm for electrical power distribution systems. This algorithm takes into account system reconfigurations. The usefulness of the proposed algorithm is showed with numerical examples.

2 A NEW APPROACH FOR RELIABILITY EVALUATION

2.1 Reliability analysis components

2.1.1 Segment

In essence, there are two configurations in a distribution system. One consists of components that are directly responsible for transmitting power from the distribution substation to customers (lines, transformers …). The second one consists of fuses, re-closers, circuit breakers, etc.

The distribution system is sectionalized into segments by these protections and isolation components. In the following sections, the power system is not modelled in terms of components but segments. A segment is a group of components, whose entry component is a switch or a protective device.

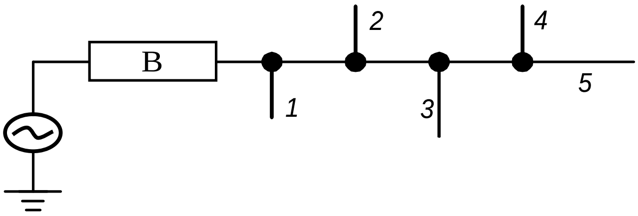

Figure 1: Sample Segment

In Figure 1, the only protection on the feeder is the station breaker. A segment's name is the same as that of its sectionalizing device. Modelling the power system in terms of segments, speeds up the reliability index calculations, since only the sectionalizing devices are processed, without processing the intermediate components.

2.1.2 *Reliability analysis sets*

In order to analyze the reliability of distribution systems, the Electric Power Research Institute (EPRI) defined sets [2] which are needed for calculating the reliability of a given load point. Figure 2 illustrates the relation among these sets.

In reliability analysis, the failure of all elements that can cause a loss of service to a particular load point must be considered. (This load point will be presented in terms of a segment, which is the segment of interest S). The failure of components not in the path can also cause an interruption at the load point, unless the component is separated from the path by a protective device that responds automatically to the component failure. The effects of non-series elements and temporary restoration are now considered in the sets shown in Figure 2, as will now be explained.

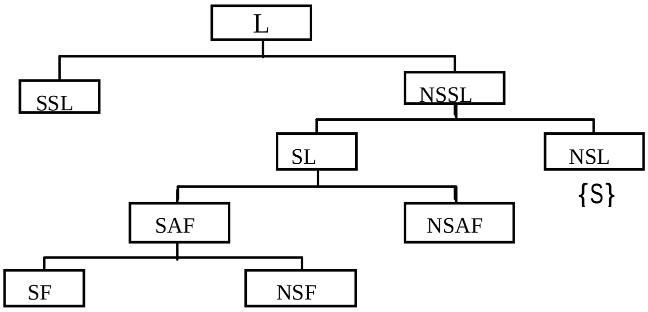

Figure 2: Reliability Analysis Sets

The L set, contains all segments within a circuit whose failure can cause loss of power to the segment of interest S. This L set includes all segments that are not separated from the continuous path between the source (substation, generator, etc) and the segment of interest S by an automatic protection device.

The SSL set consists of the segments that may be isolated from the continuous path between S and the original source; The NSSL set consists of the segments that cannot be switched away from the continuous path between S and the original source.

The SSL set contains any segments separated from the continuous path by manually operated switches. If any element of this set fails, the segment of interest S can be temporarily restored from the original source before the failed component is repaired or replaced.

The SL set consists of the segments that can be switched away from the segment of interest S, so that if the failure occurs in the SL set, S may be fed by an alternate source. The NSL set consists of the segments that cannot be switched away from the segment of interest S. That is the segment of interest itself, so this set only contains the element{S}. If any thing fails in the NSL set, all the components within that segment have to experience the full repair or replacement time of the failed component. Temporary restoration is not possible.

For the SAF set, if the failed component lies in these segments, it is possible to restore power to S by an alternate source. For the NSAF set, if the failed segment belongs to this set, the segment of interest S cannot be temporarily restored from an alternate feed. The set SAF contains the segments that can be isolated from both the segment of interest S and the alternative source, which make the temporary restoration topologically possible.

Sometimes, system constraints may limit the restoration options; the alternate source might not have the capacity to support the particular load point that of interest. So the set SAF is partitioned into SF and NSF. The SF set consists of all segments that can be isolated from S and an alternative source, allowing power to be restored to S from the alternative source (for segments in this set, system constraint violations do not occur during the restoration); The NSF set consists of all segments which may be isolated from S and an alternative source, but for which it is not possible to restore power to S because of violating system constraints.

The set L, including all the segments for calculating the reliability indices, is decomposed into a number of sets as given by

$$L = SSL \cup NSSL \quad (1)$$

$$NSSL = SL \cup \{S\} \quad (2)$$

$$SL = SAF \cup NSAF \quad (3)$$

$$SAF = SF \cup NSF \quad (4)$$

Equations (1)-(4) yield

$$L = SSL \cup SF \cup \{S\} \cup NSAF \cup NSF \quad (5)$$

To sum up, if the failed component from the L set is placed in the SSL set, it is possible to restore power to the load point of interest S from the original source. If the failure occurs in the SF set, the power can be restored to S from an alternative source without violating system constrains. But, if the failed component locates in either {S} NSAF or NSF sets, the failed component must be completely repaired before power can be restored to S.

Several additional reliability analysis (RA) sets are used to calculate the sets of Equation (5), as: SIC: set of all the segments in the circuit, SW: set of all the sectionalizing devices in the circuit, AF: set of available alternate sources, IS: set of sectionalizing devices that will isolate the segment of interest S from the original sources, NIS: set of switches that do not isolate the original source from the segment of interest, EC: set of ending components for the circuit, PD: set of protective devices in the circuit that isolate a load point of interest from its source.

2.1.3 Pointers

The pointer [3] is a variable that holds the address of a data element, it permits the construction of linked lists of data elements in computer memory [4], and they are used for all data objects. Pointers involved in reliability analysis are: Forward Pointer: forward direction for doubly linked list of circuit components. Backward Pointer: backward direction for doubly linked list of circuit components. Feeder Path Pointer: for a radial system, the feeder path pointer of a given component is the next component toward the reference substation that feeds the given component.

Because of these contained links and pointers, each component's data object is known as a "trace" structure.

2.1.4 Circuit traces

Circuit traces are applied in determining the reliability analysis (RA) sets. They employ pointers and linked lists discussed previously, and represent the order in which an algorithm processes the components of the system.

Here an overview of using circuit traces is provided using the sample circuit.

Each circuit trace represents a particular linked list tracing through the components of a circuit. These traces are defined as follows (for figure 3): FTm: forward component trace beginning with component m (if m is not specified, FT begins from the substation). As illustrated by:

FT=2→3→SW4→5→…→Fus28→29→30 (6)

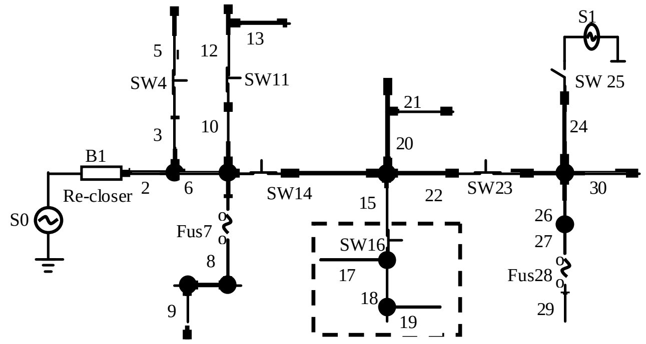

Figure 3 :Modeling in terms of Segment.

BTm =backward component trace beginning with m;

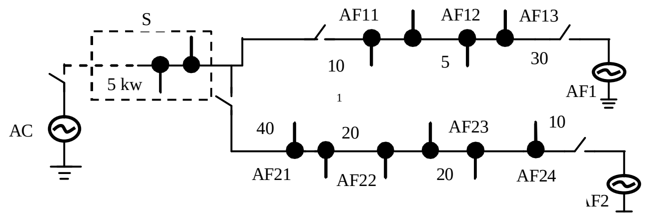

Figure 4: Selection of Alternative Feed

BT_{15}= SW14→ 13→ 12→ SW11→ →Fus7→6→5→ SW4→3→2→1 (7)

FPTm = component m's feeder path component trace, as illustrated by:

FPT_{15}= SW14→ 6→ 2→ B1 (8)

ECT = ending component trace, is given by:

ECT= 5→ 9→ 13→ 17→18→19→20→21→29→30 (9)

For reliability analysis, it is more efficient to work with pointers to segments and to perform traces based on these pointers. The segment circuit traces used in this research are: FSTm = forward segment trace from segment m, (if m is not specified, the forward trace will begin with the substation). In the example circuit, FST is given by:

FST= SW4→ Fus7→ SW11→ SW14→SW16→ SW23 →Fus28 (10)

FPSTm = feeder path segment trace (It is performed relative to a given segment m). For instance, tracing from the segment of interest, segment SW16, $FPST_{SW16}$ is given by:

$FPST_{SW16}$= SW14→ B1 (11)

AFT = alternative feed trace. In the example circuit, there is only one alternative source, so AFT is given by: AFT= SW25 (12)

If there are more than one alternative feed for the circuit, then AFT would consist of the linked list of all alternative feeds.

3 COMPUTER ALGORITHM

3.1 Reliability analysis sets calculation

The computer algorithm is used to develop the reliability analysis sets. It is assumed for the example circuit that the segment of interest is given by

{S}= {Sw16} (13)

First a forward component trace (FCT) is conducted, beginning with the substation, so that the set SW and segment pointers can be determined as.

FCT→SW, pFSeg, pBSeg, pSeg (14)

Where:

pFSeg = pointer to forward segment (in the example circuit, segment B1's pFSeg pointer is pointed to segment SW14) pBSeg = pointer to backward segment (in the example circuit, segment SW14's pBseg pointer is pointed to segment B1)

pSeg = pointer to segment device for component (in the example circuit, all the components in segment SW16, components 17, 18 and 19, have their pSeg pointed to SW16).

The expression (14) is read as the Forward Component Trace (FCT) yields the SW set and sets the pointers pFSeg, pBSeg, and pSeg.

For the example circuit,

SW= {B1, SW4, Fu7, SW11, SW14, SW16, SW23, Fu28, SW25} (15)

In the FCT, the ending components that make up the EC set can also defined, by using the following condition, If a component’s forward pointer points to its brother pointer [5], then this component is an ending component.

Thus, FCT →EC (16)

All the available alternate sources can be collected.

FCT →AF (17)

Since IS consists of all the sectionalizing devices in the feeder path of S, a FPSTs can be used to obtain the IS set, as well as the PD (protective device) set, as given by:

FPSTs →IS, PD (18)

For the segment of interest S in the example circuit:

IS={SW16, SW14, B1} (19)

PD={B1} (20)

The logic used to develop the L set is as follows:

Perform an FST, when the FST encounters a segment whose primary protective device belongs to the PD set, this segment is in the L set. Otherwise, when the FST encounters a segment whose primary protective device does not belong to the PD set, the segment is not in the L set. Thus,

FST→L (21)

Following the steps described above, the L set for the segment of interest S is obtained.

L={B1, SW4, SW11, SW14, SW16, SW23} (22)

SSL is given by the following set operations as:

SSL= L ∩ NIS (23)

Where NIS =SW- IS.

Applying Equation (23) in the example circuit, and using expressions (15), (19) and (22), the result is:

SSL= {SW4, SW11, SW23} (24)

The SL set is given by the following set operation.

SL= L ∩ IS-{S} (25)

In the example circuit, applying expressions (13) to (19) and (22), this gives:

SL={B1, SW14} (26)

In order to find the SAF set, we conduct feeder path segment traces both from an alternate source and the segment of interest S, $FPST_{AF}$ and $FPST_{S}$, respectively. When these traces encounter a common path, then the SAF set is not empty. The SAF set includes the segments in the common path except the first segment that the feeder path traces meet in the common path. Thus,

$FPST_{AF}$, $FPST_{s}$ →SAF (27)

In the example circuit,

SAF={B1} (28)

The NSAF set is given by set operation:

NSAF= SL - SAF (29)

Using expression (26) and (28), this yields:

NSAF={SW14} (30)

To achieve the SF set, the power required by S must be compared to the minimum remaining capacity of the components along the feeder path from the alternative feed[6,7] (AF).

If there is more than one alternative feed in the system, the minimum capacities encountered in the feeder path component traces FPT_{AF} for all the available sources in the AF set must be compared. For instance, there are n alternative feeds in the system. Let: C_{AFk} = minimum remaining component power capacity in the FPT_{AF} for the kth alternative feed

k=1,2,3…n. (31)

$C_{AFm} = \max_k\{C_{AFK}\}$ (32)

Thus C_{AFm} represents the greatest minimum remaining capacity available among the alternative sources. For example, as demonstrated in Figure 4, there are two alternative sources, AF1 and AF2. As indicated in the figure, the power required by S is 5 kw. The numbers on the alternative feed components stand for the remaining capacity (units of kw) of the components. According to Equation (31) and (32),

$C_{AF1}=\min\{10, 5, 30\}=5$

$C_{AF1}=\min\{40, 20, 20, 10\}=10$

$C_{AFm}=\max\{C_{AF1}, C_{AF2}\}=10$

So $AF_m=AF_2$ (33)

In order to get the required power or remaining capacity of a component, a power flow needs to be calculated. Once the power flow calculation is completed, then:

FPT_{AF} → SF or NSF (34)

In the example circuit, assuming system constraints are not violated,

SF = {B1} (35)

3.2 Reliability indices

The availability of component functionally is characterized by the annual Failure Rate: the annual average frequency of failure, and the annual Down Time: the annual outage duration experienced at a load point.

The failure rate for segment i, FRi, is the sum of the failure rates of all the components contained in the segment i as given by

$$FR_i = \sum_{j=1}^{n} Fr_j \tag{36}$$

Where: Frj = the failure rate for component j, and n = the number of components in segment i. The average repair time for a segment i, REPi, can be calculated by Where: Frj = the failure rate for component j, and n = the number of components in segment i. The average repair time for a segment i, REPi, can be calculated by

$$REP_i = \frac{\sum_{j=1}^{n} (Fr_j \times Rep_j)}{\sum_{j=1}^{n} Fr_j} \tag{37}$$

Where, Frj: the failure rate for component j, Repj: the average repair time for component j, and n: the number of components in segment i.

Once the reliability analysis sets [8] for the S, reliability indices can be calculate. It is assumed there is a single failure incident. The down time of S is.

$$DT_s = \sum_{\substack{i \in NSL, \\ NSAF, \\ NSF}} (FR_i \times REP_i) + \sum_{\substack{i \in SSL, \\ SF}} (FR_i \times SOT_i) \tag{38}$$

Where: SOTi = switch operation time to re-supply segment S due to the failure of segment i.

The customer average interruption duration index (CAIDI) for a segment is the same as DTs.

$$\text{CAIDI} = \text{DT}_s \tag{39}$$

Once the down time for each segment is calculated, and given the number of customers attached to each segment, the total customer down time, DTC, for a given circuit can be calculated by:

$$DTC = \sum_{i \in Circuit} (DT_i \times C_i) \tag{40}$$

Where Ci = the number of customers attached to segment i.

Since the failure rate and down time is known at each segment on the feeder, the system index SAIDI (System Average Interruption Duration Index) is then given by:

$$SAIDI = \frac{DTC}{\sum_{i \in Circuit} C_i} \tag{41}$$

The average restoration time for segment S is:

$$RT_s = \frac{DT_s}{\sum_{i \in L} FR_i} \tag{42}$$

3.2.1 Relative reliability index

A new measure of reliability referred to as 'Relative_CAIDI'. It helps to identify the areas that need improvement. Relative_CAIDIj is given by:

$$Relative\_CAIDIj = \frac{CAIDI_{ckt}}{CAIDI_j} \tag{43}$$

Where: $\text{CAIDI}_{\text{ckt}}$: average CAIDI for the circuit of interest, CAIDIj: CAIDI for segment j. Thus: If Relative_CAIDIj = 1, the customers in segment j have average reliability, if Relative_CAIDIj <1, the reliability is less than average and if Relative_CAIDIj >1, the reliability is better than average.

4 CASE STUDIES

The reliability is investigated for two cases (Figure 5), for a system with one source supply, after that a second source is added at the load point screening how the reliability of the interest load point [9,10] is improved. The segment of interest is SW36, all types of switches and lines respectively have a failure rates 0.001, 0.01, and all the components having a repair time of 5 hours/year.

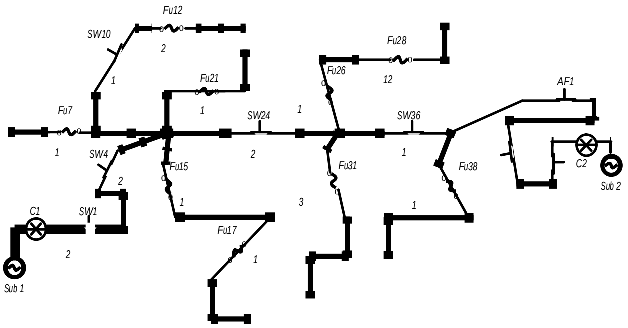

Figure 5: Case studies

4.1 One source system supply (Sub1)

Applying set Equations (13–20) relative to segment SW36 gives

L= {SW1, SW4, SW10, SW24, SW36}

SSL= {SW10}

NSSL= {SW1, SW4, SW24, SW36}

NSL= {SW36}

SL= {NULL} and

SF= NSF= NSAF= {NULL}

For this case the DT_{SW36} is 0.695 hours.

4.2 Two sources system supply (adding Sub2)

Again, applying the set equations (13–20):

L= {SW1, SW4, SW10, SW24, SW36}

SSL= {SW10}

NSSL= {SW1, SW4, SW24, SW36}

NSL= {SW36}

SL= {SW1, SW4, SW24}

SAF= {SW1, SW4, SW24}

NSAF= {NULL}

SF= {SW1, SW4, SW24}

NSF= {NULL}

With the alternate source, the DT_{SW36} is reduced to 0.1865 hours, nearly one seventh of the DT_{SW36} in the original system. In this case SW36 does not need to wait for the failing component to be repaired. The DT_{SW36} will be the switch operation time instead of the repair time for the failing component. The reliability of the entire system is improved. Table1 shows a comparison of reliability indices for the two cases. The number attached to the segment in figure5 is the number of customers in each segment. Table 2 shows the improvement of DT for all the segments in circuit C1.

Table 1: Improvement of System Reliability

Reliability Indices	Without Alt Feed	With Alt Feed	Improvement
SAIDI Hrs/yr)	0.64231	0.39132	39.076%
CAIDI Hrs/yr)	2.3442	1.4282	39.075%

Table 2: Comparison of Reliability Improvements

Segment	Down Time (Hrs/yr)		Improvement
	Without Alt Feed	With Alt Feed	
SW1	0.2315	0.2315	0 %
SW4	0.4655	0.371	20.30 %
Fu7	0.515	0.4205	18.34 %
SW10	0.4745	0.38	19.91 %
Fu12	0.5645	0.47	16.74 %
Fu15	0.515	0.4205	18.34 %
Fu17	0.6095	0.515	15.50 %
Fu21	0.515	0.4205	18.34 %
SW24	0.6455	0.317	50.89 %
Fu26	0.695	0.3665	47.26 %
Fu28	0.7445	0.416	44.12 %
Fu31	0.785	0.4565	41.84 %
SW36	0.695	0.1865	73.16 %
Fu38	0.7895	0.281	64.40 %

5 CONCLUSIONS FROM THE INVESTIGATIONS ARE

If the failure happens in the set SAF, SW36 can be restored from circuit C2 without violating system constraints, because Sub2 has plenty of capacity to support its adjacent circuit. The set NSF is empty, so SF=SAF.

With the alternate source, the annual down time for SW36 is reduced to 0.1865 hours, nearly one seventh of the annual down time in the original system. The significant drop comes from power being restored from Sub2, and SW36 does not need to wait for the failing component to be completely repaired. In this case, the down time will be the switch operation time instead of the repair time for the failing component.

If the load on circuit C2 becomes heavier, substation Sub2 might lose the capacity to pick up the load on C1. For example, when the line (where the alternative feed is connected) is prolonged or a load is added to it, pushing the load near to the overload point for the line, the annual down time for segment SW36 will jump back to 0.695 Hrs/yr, and the system CAIDI will also go back to 2.3442 Hrs/yr. It means the load point of interest cannot be restored from the alternate source because system constraints will be violated. Now it can be seen how the availability of alternate feeds and the change of the system loading impact the system reliability

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