Calculating Electrical Risk and Reliability

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Abstract - With increased emphasis on reliability and cost control, we are striving to achieve more reliable electrical systems and at the same time minimize the costs associated with building, operating, and maintaining them. This paper covers the details of an easy to use PC computer model that can calculate the availability and reliability of electrical systems and can determine the cost impact due to loss of production associated with the failure of a segment of the system.

I. Introduction

For many years when engineers talked about the reliability of electrical systems, they often used non-specific quantifiers such as "Good, Better, Best", or "what we propose is better than what you have", or "if we don't do something soon, it will probably fail and cause tremendous problems". If they did try and get more scientific, they usually would drag out the IEEE Gold Book [1] and dig through it trying to make heads or tails about how the reliability calculations worked and then try to figure out which piece of information from the mounds of data in the book should be used to represent the problem at hand. At the 1992 PCIC Conference, one author raised many important issues about how and why conceptual models of systems must be developed long before attempting to build and design them [2]. One of the key points emphasized was the need to speak the language of the business community. In today's world, this language is centered around such factors as business risk, cost impact, first cost, life cycle cost and the cost to operate and maintain. Notice that the language almost always deals with cost and is based on actual data. It may well be a waste of time if electrical reliability is discussed in a language other than cost and in a context based on something other than fact-based data. To have meaningful results from an electrical reliability evaluation, **the answer must be in dollars**. When performing electrical reliability studies, the dollars most often dealt with are not the costs to build, operate and maintain the electrical systems, but rather the costs associated with the loss of production when the system fails. These costs, in turn, justify the cost to build and operate the appropriately designed systems. With these thoughts in mind, here is the description of the problem that we were trying to solve**:** *Develop a modeling tool that an engineer can apply to both new and existing real life electrical systems that will help determine the reliability at any point in the system and will determine the cost impact from loss of production.* While not absolutely necessary, it was also highly desirable to have a tool that was fast, reasonably accurate and simple to apply to all electrical distribution systems.

II. Modeling Background and Approaches

The first analytical modeling used at the author's company was developed out of a demand by senior management to achieve 95% availability of all major process facilities. In order to achieve this, information was needed to understand what impact electrical facilities had on these units and to also understand what could reasonably be expected from the existing systems. The 95% availability demand did not include planned turnarounds, which were estimated to be 3%, resulting in a 98% actual availability demand. Of the remaining 2%, 1% was allocated to problems associated with operating issues. This left 1%. Of that 1%, 0.5% was allocated to mechanically related problems and 0.2% was allocated to electrical problems. Using simple mathematics 0.2% of one year is about 18 hours. In order to meet business requirements, the impact of all electrical failures to the operation of a unit had to be less than 18 hours per year. Intuitively, this did not seem achievable in some facilities, but a way was needed to demonstrate that and to analyze what needed to be done to correct deficiencies. The first PC model was built primarily on principles derived from the Gold Book. It analyzed six electrical components in a relatively simple radial power distribution system. While simple in nature, the model was able to provide analytical results which demonstrated that the existing system could not achieve the desired availability. Second and even more importantly, it was able to demonstrate the cost impact associated with a loss of production that an electrical system failure had on the connected operating facilities. Another important feature was that being a spreadsheet, "what if" analysis could be performed to see the impact of component reliability.

The next step was to refine and apply the technique to a large integrated facility that had five different incoming sources of power plus internal generation. The scope of the model was increased to include 20 different electrical components. A three-month effort resulted in the analysis of reliability and cost impact at over 60 different locations within the plant. The modeling technique had achieved most of the desired objectives, except in two areas. First, it was quite limited on the number of different electrical components that could be modeled. Second, it was a very time consuming and demanding technique that required significant training and practice to master.

In an effort to overcome the complexity of customizing a model for every system, several thoughts came to mind. The first was to try and adopt one of the many commercially available system study programs to calculate reliability. The thought was that instead of having impedance values in the libraries, one could substitute failure and repair values. The models already knew the configuration of the system and could do a high tech. system analysis and come up with the results. After all, failure rates for series and parallel systems combine in a manner very similar to that of impedances. The only problem with this approach was that while an array of electrical components may be physically connected in parallel, their reliability equivalent model may have the components connected in series. For example, if there is a pole line running along Main Street with service drops into several customers, the one line would show all the customers service drops in parallel off the pole line. Yet when one customer has a fault on their service drop, all of the other customers also lose their power until the problem can be isolated and repaired. Thus, when representing the reliability of all the service drops, they end up being in series.

As additional models were created using this older technique, it was soon realized that the failure rates at points in a system between protective devices such as circuit breakers, reclosures, or fuses were the same. With this thought, a new technique was developed in which the electrical distribution system was divided into zones.

Zones are defined as a segment of a power distribution system in which a fault at any location within the segment or zone would have the common impact of causing the first upstream protective device to isolate the system.

Relating this to a typical household electrical system, a zone would be all the parts of a branch circuit supplied from one circuit breaker. If a fault or overload occurs anywhere in the zone, the breaker will trip and there will be a loss of power to everything supplied by the breaker. It doesn't matter where in the zone the fault is, the result is the same; power is lost to everything connected within the zone. In developing this modeling technique, a way was needed to describe each of these zones, to link all of the zones together, and to describe the failure rate at any point within the system. Last, a way was needed to convert all of these results into costs per incident, cost per year, mean time between failure and mean time to repair. As mentioned earlier, the results had to be in the business language of dollars.

The concept of developing reliability zones is quite similar to the technique used in protective relaying for describing zones of protection. This should not come as a surprise. One of the primary purposes for protective devices from a system's standpoint is to improve reliability by isolating faulty components while minimizing the impact to the remainder of the system. A few new terms needed to be defined as the model was being developed.

The term *Point* was defined as any place or location within the electrical system. Point X is any place or location within Zone X. Typically within a system a *point* is a source of electrical energy for the *zone(s)* connected below or downstream of it.

When defining the configuration of a system, a *Zone* can be configured either in series with the *Point* immediately above it, or a *Zone* can be configured in parallel with the two *Points* immediately above it. An example demonstrating this concept is presented later in this paper.

The model determines the failure rate and repair rate of all components within a *Zone* without taking into consideration that the *Zone* is connected to any other portion of the system. The model then determines the failure rate and repair rate for all the *Points* in the system by taking into consideration the configuration of all the *Zones*. The model includes a matrix called the **Zone Table** in which the configuration of the *Zones* is entered. In developing the output portion of the model, another matrix table, called the **Unit Impact Table,** allows the entry of various connected process units or loads and the impact that each *Point* has on the unit or load. It also includes data entry to reflect the cost impact for not having the unit available for 24 hours. The last data entry field is the time it will take to get the process unit or load restreamed from a cold start. The model has a simple technique to determine if the unit has been down long enough to become "cold". For most process units, the time required to restream the unit following a failure is relatively short if the problem can be corrected quickly. However, if the repair persists for an extended period of time, the unit will get "cold" and restreaming of the unit may take much longer. The model also has a results section labeled the "Model Component Summary". Here the total quantity of each electrical component is displayed along with the expected failure rate for that population of components. The summary also includes the total number of components within the model and the failure statistics for the entire population of components.

III. Definitions

Annual Risk - The calculated financial losses of production due to an electrical system failure divided by the frequency (MTBF) of the failure.

Availability - A ratio that describes the percentage of time a component or system can perform their required function.

Component - A piece of electrical or mechanical equipment, a line or circuit, or a section of a line or circuit, or a group of items that is viewed as an entity for the purpose of reliability evaluation.

Failure - The termination of the ability of an item to perform a required function.

Failure rate - The mean number of failures of a component per unit exposure time.

Forced downtime - The average time per year a system is unavailable in between failures and expressed in hours per year.

Lambda (l) - The inverse of the mean exposure time between consecutive failures. Lambda is typically expressed in either failures per year or failures per million hours.

MTBF - The mean exposure time between consecutive failures of a component or system. The mean time between failures is usually expressed in either years per failure or million hours per failure. For some applications measurement of mean time between repairs (MTBR) rather than mean time between failures may provide more statistically correct information.

MTTR - The mean time to repair a failed component. For a system, it is the total amount of time it is unavailable in between failures and is expressed in hours in both cases.

Point - Any place or location within the electrical system. The name or designation for a point is always the same as the name of the zone that the point is located within.

RAM Table - A lookup table in the model that displays the MTBF and MTTR for electrical components.

Reliability - An indication of the ability of a component or system to perform its intended function during a specified time.

Restore Time - In the model, the time to restore is the sum of the mean time to repair (MTTR) for the failure plus the computed time to restream or restart the connected process unit or load.

System - A group of components connected or associated in a fixed configuration to perform a specified function of distributing power.

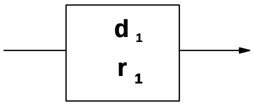
Zone - A segment of a power distribution system in which a fault at any location within the segment or zone would have the common impact of causing the first upstream protective device to isolate the system

IV. Theory Behind Model

The reliability calculations that the model is based on are relatively straightforward and can be found in most textbooks on the subject. The following is a brief description of the computations used when combining zones in series and parallel.

A. *Single Component Analysis*

Reliability and availability are necessary to describe the characteristics of the single component shown.



$\mathbf{d_1 = MTBF}$ (in hours)
$\mathbf{r_1 = MTTR}$ (in hours)

Reliability of components is frequently given as failures per million hours of operating time. Using these numbers, the Mean Time Between Failure (MTBF) can be calculated using:

$$\mathbf{d_1 = MTBF\ \ (in\ hours)}$$

$$d_1 = 10^6 / (\text{failures} / 10^6 \text{ hours})$$

The failure rate Lambda (λ) is given by:

$$\lambda = 1 / MTBF$$

and the component reliability (R_1) for one year is given by:

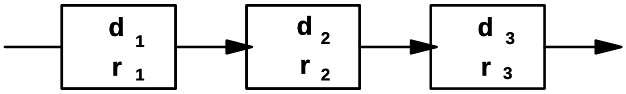
$$R_1 = e^{-(\lambda)(8760)}$$

For a single component, the availability (A) is given as the total operating time over the total time, or:

$$A = (MTBF) / (MTBF + MTTR)$$

B. *Systems with Components in Series*

For the system shown with three different components in series,



d = MTBF (in hours)

r = MTTR (in hours)

The characteristics of each individual component can be calculated using:

$$\lambda_i = 1 / d_i$$

$$A_i = d_i / (d_i + r_i)$$

$$R_i = e^{-\lambda_i t}$$

$$R_i = e^{-\lambda_i (8760)} \quad \text{for one year}$$

Using these, the combined failure rate (failures per year) becomes:

$$\lambda_S = \lambda_1 + \lambda_2 + \lambda_3$$

or

$$\lambda = R_1 * R_2 * R_3$$

Reliability of the system for one year:

$$R_S = e^{-\lambda S(8760)}$$

System availability :

$$A_S = A_1 * A_2 * A_3$$

Probability of failure during one year:

$$P_S = (1 - R_S) * 100$$

MTBF:

$$MTBF = 1 / \lambda_S$$

MTTR in hours:

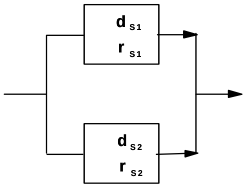
$$MTTR = MTBF\ [(1 / A_S) - 1]$$

Forced downtime:

$$FDT = (1 - A_S)$$

C. ***Systems with Redundant Components***

1) *Redundant Active Systems - Non-repairable* : Reliability can be dramatically increased by installing a parallel (redundant) system. The simplest of these is a system that operates satisfactorily if either one of two parallel components functions.



The reliability for such a system for one year can be calculated using:

$$R_S = [\,1 - (1 - R_{S1})(1 - R_{S2})]$$

the combined failure rate is:

$$\lambda_S = \ln\,(1 / R_S)$$

the system availability is:

$$A_S = [\,1 - (1 - A_{S1})(1 - A_{S2})$$

and the probability of failure during one year is:

$$P_S = (1 - R_S) * 100$$

2) *Repairable Redundant Systems*: If the components can be repaired, the reliability of the systems described above also becomes a function of the time required to repair the system.

Using a constant failure rate for two identical units, the steady-state availability is:

$$A = \mu \,/\, \lambda + \mu$$

where the repair rate (μ) is (MTTR) -1

and the MTBF is:

$$MTBF = \mu \,/\, (2\lambda^2)$$

For two different components in parallel, the MTBF is:

$$MTBF = (\lambda_a + \mu_b)(\lambda_b + \mu_a) + \lambda_a(\lambda_a + \mu_b) + (\lambda_b + \mu_a) \,/\, \lambda_a\lambda_b(\lambda_a + \lambda_b + \mu_a + \mu_b)$$

and the steady-state availability for n blocks is:

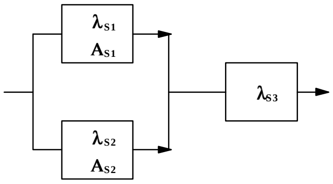
$$A = 1 - \prod_{i=1}^{n} (\lambda_i \,/\, \lambda_i + \mu_i)$$

or for two parallel Components:

$$A = 1 - [(\lambda_1 \,/\, (\lambda_1 + \mu_1))(\,\lambda_2 \,/\, (\lambda_2 + \mu_2))]$$

D. ***Common Cause***

Redundancy calculations frequently lead to reliability numbers that are outside the realm of reason, for example one failure in a thousand years. In reality, even redundancy of components still leaves a chance that the parallel system will fail from a common mode. Examples of this include common electrical connections, common alarm wiring, or the environment. One suggested method [3] to account for common failure modes is to use an additional component in series with the redundant system as shown below.

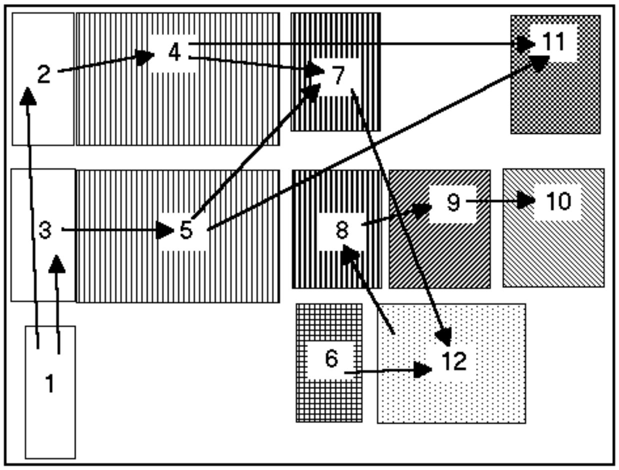


A reliability of between 0.01 and 0.1 times the reliability of the components in the individual redundant components seems to provide results that are comparable with actual experiences. The default value in the model is 0.1.

V. Overview of Model

The electrical reliability model is a Microsoft Excel (TM) spreadsheet. The 70 zone model is 230 columns wide by 286 rows tall.

Before getting into some of the details of the model, it may be helpful to get an overall picture of the layout of the spreadsheet. **Fig. 1** below shows the relative position of the various major areas of the model.

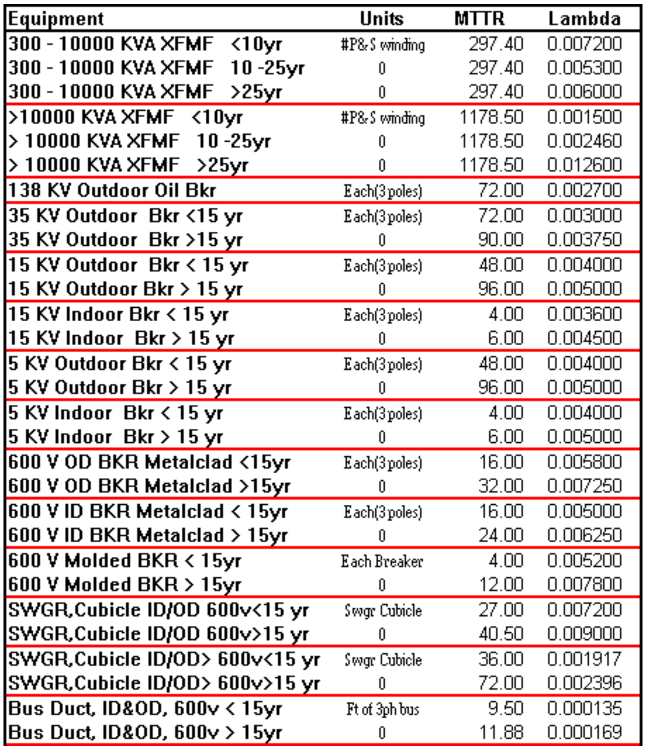


1 - RAM Table Master
2 - RAM Table for Zones 1 - 35
3 - RAM Table for Zones 36 - 70
4 - Quantity Input for Zones 1 - 35
5 - Quantity Input for Zones 36 - 70
6 - Zone Table for Configuration
7 - Zone Calc Table for Zone Results
8 - Point Calc Table for Point Results
9 - Unit Impact Table for Financial Impact
10 - Consequence Table for Model Results
11 - Model Component Summary
12 - Misc. Point & Configuration Calculations

Fig. 1 Model Layout

A. ***RAM Table***

The RAM table is the data base that contains the electrical component reliability data. The data can be manually changed or updated to fit the users specific needs. A change in the Master RAM table data will be reflected throughout the entire model. **Table 1** is an example of the first 29 rows of a typical RAM table. The RAM table has 84 rows to enter different electrical components.



Equipment	Units	MTTR	Lambda
300 - 10000 KVA XFMF <10yr	#P&S winding	297.40	0.007200
300 - 10000 KVA XFMF 10 -25yr	0	297.40	0.005300
300 - 10000 KVA XFMF >25yr	0	297.40	0.006000
>10000 KVA XFMF <10yr	#P&S winding	1178.50	0.001500
> 10000 KVA XFMF 10 -25yr	0	1178.50	0.002460
> 10000 KVA XFMF >25yr	0	1178.50	0.012600
138 KV Outdoor Oil Bkr	Each(3 poles)	72.00	0.002700
35 KV Outdoor Bkr <15 yr	Each(3 poles)	72.00	0.003000
35 KV Outdoor Bkr >15 yr	0	90.00	0.003750
15 KV Outdoor Bkr < 15 yr	Each(3 poles)	48.00	0.004000
15 KV Outdoor Bkr > 15 yr	0	96.00	0.005000
15 KV Indoor Bkr < 15 yr	Each(3 poles)	4.00	0.003600
15 KV Indoor Bkr > 15 yr	0	6.00	0.004500
5 KV Outdoor Bkr < 15 yr	Each(3 poles)	48.00	0.004000
5 KV Outdoor Bkr > 15 yr	0	96.00	0.005000
5 KV Indoor Bkr < 15 yr	Each(3 poles)	4.00	0.004000
5 KV Indoor Bkr > 15 yr	0	6.00	0.005000
600 V OD BKR Metalclad <15yr	Each(3 poles)	16.00	0.005800
600 V OD BKR Metalclad >15yr	0	32.00	0.007250
600 V ID BKR Metalclad < 15yr	Each(3 poles)	16.00	0.005000
600 V ID BKR Metalclad > 15yr	0	24.00	0.006250
600 V Molded BKR < 15yr	Each Breaker	4.00	0.005200
600 V Molded BKR > 15yr	0	12.00	0.007800
SWGR,Cubicle ID/OD 600v<15 yr	Swgr Cubicle	27.00	0.007200
SWGR,Cubicle ID/OD 600v>15 yr	0	40.50	0.009000
SWGR,Cubicle ID/OD> 600v<15 yr	Swgr Cubicle	36.00	0.001917
SWGR,Cubicle ID/OD> 600v>15 yr	0	72.00	0.002396
Bus Duct, ID&OD, 600v < 15yr	Ft of 3ph bus	9.50	0.000135
Bus Duct, ID&OD, 600v > 15yr	0	11.88	0.000169

Table 1 Example of RAM Table

The first column is a listing of the equipment description. The second column is the units used for counting the equipment. For example transformers are counted by per winding. A standard two winding transformer is counted as two devices and a three winding transformer is counted as three devices. Equipment that typically is supplied as a three phase device such as a vacuum circuit breaker is counted as one device for each three-pole unit. Note that this is not a standard convention for counting equipment. However, one must agree upon some method for the MTTR and MTBF to have any true meaning. The third column is the Mean Time To Repair (MTTR) a component. It is the average time in hours required from the time of the fault until the component is repaired or replaced and ready to be placed back into service. There are many factors that can influence this number such as the availability of parts, crafts, service shops, etc. The last column is the failure rate (Lambda or 1/MTBF). It is the number of component failures per unit year. This data is typically obtained either from the Gold Book or is based on actual plant experience.

B. ***Zone Data***

Each Zone has a visible column for entering the quantity of electrical components within that zone. When entering data into a model, one typically splits the screen to view both the RAM Table and the Zone Data. Each zone also has several “hidden” columns that perform background calculations.

C. ***Zone Calculation Table***

The Zone Calculation Table is an area where combined reliability calculations are made for all the components within each zone.

D. ***Zone Table***

The Zone Table provides the format for entering the configuration of the electrical system into the model. It is based on the premise that each zone is either connected in series to one upstream point, or is connected in parallel upstream to two points. The model takes this input and calculates additional reliability parameters for each point.

E. ***Point Calc Table***

The Point Calc Table is the location where all of the calculated results pertaining to each individual point are assembled.

F. ***Unit Impact Table***

The Unit Impact Table is a data entry table that is used to tabulate the financial impact that the failure of a point will cause.

G. ***The Model Component Summary***

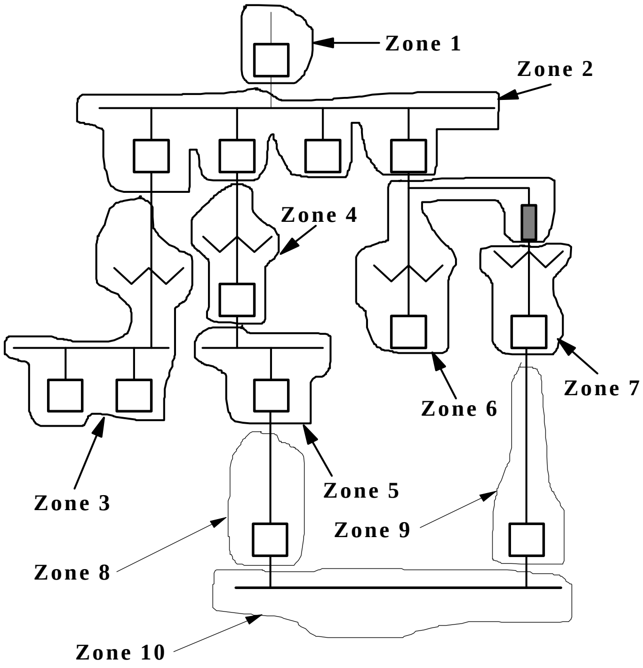
The Model Component Summary Table displays statistical information about each type of component used in the model.

VI. Model and Data Entry

Before entering data into the model, the zones must be defined. The technique that is normally used is to draw a circle around sections of the one-line from the bottom or load side of a protective device down to and including the bottom or load side of the next downstream protective device. **Fig. 2** is an example of how zones are added to a one-line.

Note that there is a zone change at each fuse and breaker. However, the zone for the branch on the left side without any fault protective devices at the transformer includes both the high and low voltage busses.

Once the zones have been defined, the quantity of each component listed in the RAM table for each zone must then be counted. The quantity is entered into the "Quantity Input" section of the spreadsheet.



Adding Zones to One-Line

Fig. 2

A. *System Configuration & Zone Table*

Once the quantity of components for every zone has been entered, the configuration of the zones or system is entered into the spreadsheet. This is done in the Zone Table. The actual configuration of the system could be reconstructed without the one-line from the data in the Zone Table. **Table 2** below shows what the Zone Table would look like for the sample system shown in **Fig. 2**. Note that Zone 10 is the only common zone (CZone) on the model that is connected in parallel with two sources. Note that Zone 1 is connected to Point 0, which is an Infinite point with unity reliability that is used as a starting point.

	Series Zone	Point	Parallel CZone	Point "1"	Point "2"
point1	1	0			
point2	2	1			
point3	3	2			
point4	4	2			
point5	5	4			
point6	6	2			
point7	7	2			
point8	8	5			
point9	9	7			
point10			10	8	9

Sample Zone Table for Model Shown in Fig. 2

Table 2

After data is entered into the Zone Quantities and the Zone Table, the spreadsheet will calculate all of the reliability related parameters for each zone and point. However, before discussing the output, there are a few more inputs that need to be entered. The spreadsheet default Common Cause value of 0.100 can be changed to reflect the common failure modes of the specific system.

B. *Unit Impact Table*

The unit impact cost table allows ten process units or loads to be listed. The cost impact for having each unit down for a 24-hour period is then entered into the Unit Impact Table. In the matrix, the impact that a failure of each individual point will have on the listed unit is entered. The impact is entered as a percentage (1 to 100) of the 24-hour cost impact. The percentage can reflect both direct impacts associated with a loss of power and indirect impacts such as the shutdown of a downstream unit because of the loss of the unit supplied by the point in question.

Data must now be entered to model the time required to restart a process unit or load once the electrical failure has been repaired. Entering this information completes the data entry for the case study.

VII. Output Information

The Zone Calc Table presents the reliability related statistics for each individual zone. The usefulness of this data is that **individual zones that have unusually high or low failure statistics can easily be spotted**.

In a similar fashion the performance at each point can be reviewed. The Point table displays the reliability related statistics for each point in the system, taking into account the configuration of the system as described in the Zone Table. In comparing the data shown on the Zone Calc table and the data shown on the Point Table , the impact of having all the system components connected together can be seen.

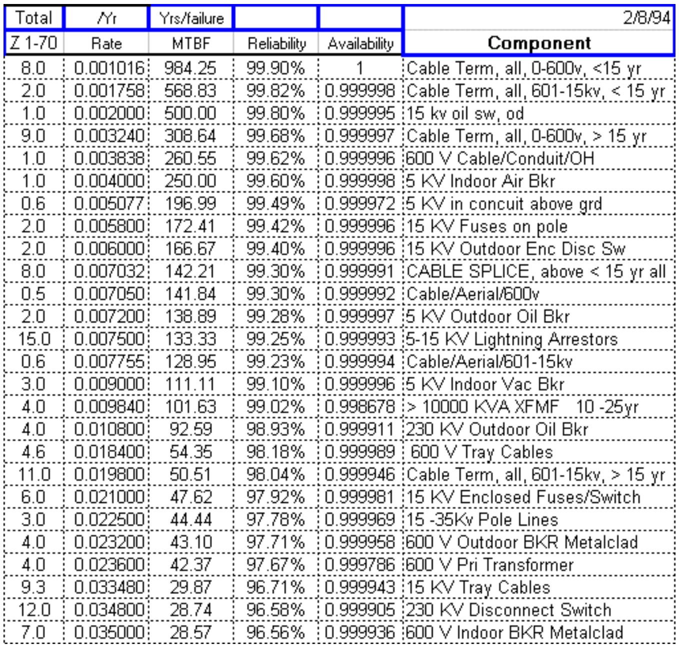
A. *Consequences Table*

The Consequence Table presents a tabular summary of the reliability and financial impact for each point. The table has a column that shows the calculated cost for the loss of each point for which financial impact was entered Another column displays the total hours per year that the point will be down, the cost in dollars for this downtime for each incident, and the annual financial risk associated with lost production associated with each point.

B. *Model Component Summary*

The Model Component Summary Table provides a summary of all the components used in the system model, the combined failure statistics for each component and some component statistics for the entire system. A small table is located at the bottom of the component summary that displays some overall system information.

It is often desirable to copy the value of the results from the various output tables to a different spreadsheet and then sort and analyze the information and generate reports. **Table 3** is a sample of the first few lines of a Model Component Summary Table that was sorted by MTBF in decending order. This reflects the failure rates that the facility should experience for each type of component. If modeled correctly, this data should compare with actual plant experience.



Total	/Yr	Yrs/failure			2/8/94
Z 1-70	Rate	MTBF	Reliability	Availability	**Component**
8.0	0.001016	984.25	99.90%	1	Cable Term, all, 0-600v, <15 yr
2.0	0.001758	568.83	99.82%	0.999998	Cable Term, all, 601-15kv, < 15 yr
1.0	0.002000	500.00	99.80%	0.999995	15 kv oil sw, od
9.0	0.003240	308.64	99.68%	0.999997	Cable Term, all, 0-600v, > 15 yr
1.0	0.003838	260.55	99.62%	0.999996	600 V Cable/Conduit/OH
1.0	0.004000	250.00	99.60%	0.999998	5 KV Indoor Air Bkr
0.6	0.005077	196.99	99.49%	0.999972	5 KV in concuit above grd
2.0	0.005800	172.41	99.42%	0.999996	15 KV Fuses on pole
2.0	0.006000	166.67	99.40%	0.999996	15 KV Outdoor Enc Disc Sw
8.0	0.007032	142.21	99.30%	0.999991	CABLE SPLICE, above < 15 yr all
0.5	0.007050	141.84	99.30%	0.999992	Cable/Aerial/600v
2.0	0.007200	138.89	99.28%	0.999997	5 KV Outdoor Oil Bkr
15.0	0.007500	133.33	99.25%	0.999993	5-15 KV Lightning Arrestors
0.6	0.007755	128.95	99.23%	0.999994	Cable/Aerial/601-15kv
3.0	0.009000	111.11	99.10%	0.999996	5 KV Indoor Vac Bkr
4.0	0.009840	101.63	99.02%	0.998678	> 10000 KVA XFMF 10 -25yr
4.0	0.010800	92.59	98.93%	0.999911	230 KV Outdoor Oil Bkr
4.6	0.018400	54.35	98.18%	0.999989	600 V Tray Cables
11.0	0.019800	50.51	98.04%	0.999946	Cable Term, all, 601-15kv, > 15 yr
6.0	0.021000	47.62	97.92%	0.999981	15 KV Enclosed Fuses/Switch
3.0	0.022500	44.44	97.78%	0.999969	15 -35Kv Pole Lines
4.0	0.023200	43.10	97.71%	0.999958	600 V Outdoor BKR Metalclad
4.0	0.023600	42.37	97.67%	0.999786	600 V Pri Transformer
9.3	0.033480	29.87	96.71%	0.999943	15 KV Tray Cables
12.0	0.034800	28.74	96.58%	0.999905	230 KV Disconnect Switch
7.0	0.035000	28.57	96.56%	0.999936	600 V Indoor BKR Metalclad

Table 3 Sample Model Component Summary

VIII. Results Achieved

One of the first things realized in developing the modeling techniques was that there had been and continues to be a great deal of study performed by the utility industry in trying to understand the reliability associated with power generation and distribution [4], but there has been much less information available on how to analyze power distribution systems within manufacturing plants. The IEEE Gold Book continues to be the prime reference with additional theoretical information from the more classic textbooks.

It was also discovered at the author's company, that some people were very familiar with statistical analysis and some people were very familiar with electrical distribution systems, but there were not any people familiar with both. It was a new learning experience to try and apply science to understand the failure rates of electrical equipment and systems and the financial risk impact that they have on business.

The whole topic of failure and repair rates associated with electrical equipment became an area of discussion. As a result of these discussions, the RAM Table, with its MTBF and MTTR for the electrical components, has undergone more changes than any other portion of the model. On the very first model created, the table was quite simple. It consisted of about a half dozen failure and repair rates taken directly from the Gold Book. Soon there were discussions surrounding the methodology for counting components, how to distinguish between new and old equipment, how to distinguish between well versus poorly maintained equipment, and how to capture the many different types of components used in a typical facility. The RAM Table has evolved into a data base representing both "new" and "old" components. In addition, multiplying factors for the MTTR and Lambda were added to later versions of the model to provide the user options to account for the quality of preventative maintenance and the ability of the facility to execute timely repairs.

As the model evolved and was being applied to the analysis of projects for upgrading old facilities with newer equipment, the comment "Our plant data is different than what you show in the model" repeatedly came up. The typical reply was, "The data in the model is from the Gold Book and it's the best we have right now, but if you have better documented data, just change the data in the model to reflect your experience". Having a spreadsheet model was very advantageous from this standpoint. From this ongoing change of the RAM Table, two things have been learned. First, the electrical industry is well ahead of many other segments of industry by having data such as that found in the Gold Book for analyzing the failure of electrical equipment. Some narrow segments of industry such as the electric utility and nuclear have very good data, but this is not universally the case. Second, even with the Gold Book data, recent information from the author's plants indicates that the company's own failure experience, if not that of all the industry, has changed significantly over the past few years. When analyzing entire facilities, the author's data often deviates significantly from the Gold Book. Also, as additional models are created for existing facilities, it is becoming evident that many components currently being used in facilities today are not even included in the Gold Book. This would suggest a real need for industry to better understand the performance of the actual equipment that is now being installed and used in their facilities.

As the systems and technology have progressed quickly into an era of advanced electronics and tools for communication and monitoring, it is relatively easy to get so wrapped up in the amazement of horns, whistles, and other novel accessories that provides a link with the basic electrical devices that it is forgotten to assess if the function of a new component is better, or for that point, even equal to the performance of the device that it is replacing. Also, when dazzled by the awesome ability of some of the electronic wonders, the impact that the device will have on the repair time of the system is sometimes overlooked. A look at hardware from the different perspective of reliability and repairability tends to crystallize the importance that component and system reliability and maintainability have on the financial existence of industry and the absolute necessity that **independent of what else a product can provide, it must first be more reliable and more repairable than the product it is trying to replace or compete against**. In a segment of the industry that is based on the application of proven technology the reliability and maintainability of new products must outperform that of existing technology or its use should not be considered.

As system analysis continued, it was difficult to get that comfortable "feel" that the RAM data being used was actually correct. What was found was that for analysis of small segments of distribution systems, adequate historical data was not available and the quantity of individual components was not large enough to assure credible results. It wasn't until complete manufacturing facilities were modeled that the equipment failure data began to relate to the RAM Table data. Once entire facilities were modeled, the whole picture seemed to quickly come into focus. First, the calculated failure rates for all incidents in the facility as well as for individual points could be compared to existing data. In most cases, this could be easily compared with historical data for the past few years. Second, the model developed failure predictions for the entire population of a component within the facility and again, this could be compared to historical data. For example, it was often difficult to determine how many medium voltage cable failures or medium sized transformer failures a plant had within one process area over the past few years, but most of the plants had a good idea how many had occurred within the entire facility over the same period of time. As a result of this, the data in the RAM table has been modified several times to fit both the author's company's experience and also to fit each individual plant's experience. It has been found that the type of equipment, the availability of local repair facilities and the plant's maintenance practices all influence the performance of equipment.

Electrical system configuration plays an important role in the system's reliability. No matter what is done to improve the failure and repair rates for individual electrical components, the resulting reliability of the power distribution system will remain a function of how all the pieces are connected together. Several cases have been modeled where the end result of trying to achieve "better" reliability has actually resulted in either no appreciable improvement or worse yet, less desirable performance. One specific area where this comes about is in the application of isolation switches. It seems that everyone likes isolation switches. They provide flexibility in the operation and maintenance of distribution systems. However, what modeling analysis has shown is that at some of these facilities, one of the more significant causes for unacceptable performance of the overall system has been the failure of the isolation switches. This is not to say that all isolation switches should be eliminated. Rather, as each component is added to a distribution system, realize that it will eventually fail, and analyze the impact that the component failure will have on the system. A second example to think about is the use of normally closed tie breakers. It is very easy to realize that properly designed double ended substations with normally closed tie breakers can have a very significant impact on improving the downstream reliability. For this reason, they are used in many primary power distribution systems. However, care must be used in applying successive levels of double ended substations at lower voltage levels in plants. This isn't because of fault current problems, which could well be the case for some systems. Rather, the reason is that as double ended configurations are daisy chained one below another, the improvement in reliability of the system often quickly diminishes. As this happens the engineer must ask if the $50M to $100M required to provide this feature provides the most reliability for the investment. In some cases it may, but in many it may not. The answer isn't known without analyzing the consequences.

Financial risk associated with the loss of portions of an electrical system was another area for learning. World scale cat crackers and hydrocrackers whose loss of production is measured in hundreds of thousands of dollars a day result in very interesting studies. Even the slightest upset in one of these units can impact the overall corporate financial performance. When the financial risk associated with a power failure is analyzed, there is a good chance that sophisticated multi-source power systems can often be easily justified. There are two key elements to this statement. First, the risk must be analyzed. There is no more room for guesswork or "gut" predictions. The analysis must be based on actual data. Second, the impact must be related to financial risk. Even in a major process unit, if the failure of a component has no significant impact on the function of the unit, the focus should be shifted to a different area.

On the other end of the spectrum from the world scale unit is the little pots and pans unit that chugs along making $20,000 a day. The power distribution system is old and causing problems and the engineer would like to replace it with the latest doubled-ended, electronically-monitored model. However, after performing a risk assessment the payback is calculated to be 100 years. The engineer feels downhearted and wonders how long the plant will have to live with this junk! This is certainly not as exciting as the big stuff, but nevertheless important. What must be done in this case is to understand where limited funds can best be invested for maintaining and improving the system. Often by carefully analyzing the failure rates of the various system points coming into the facility plus the failure rates of the various zones within the facility, it will become clearer where the funds can best be invested. Since configuration often has a key role in the reliability of a system, a minor modification to the system may result in a significant change. Also, for each piece of equipment there are two key variables that can be addressed. First is the MTBF for the device. By exercising proper preventive maintenance to selected components, the life of the device can be extended. Second is the MTTR. There are several factors that can affect the repair of the device. Additional craft training, stocking or having a vendor stock critical spare parts, or planning the failure of the component prior to the event and developing a written plan for how to expedite its repair or replacement can impact the repair time.

One of the most significant changes that has been seen from the use of this model is the paradigm shift that electrical engineers are making in how they view distribution systems and the hardware used to build these systems. All too often in the past, power distribution systems have been designed for new facilities with a specific configuration and with specific components because "that's the way we've always done it". Most engineers involved in the design of the last generation of equipment knew that they did not have the tools nor the financial pressures to necessarily provide or demand the most cost effective or reliable design. The engineer of today must factor in system configuration and the components used for designing systems to minimize the financial risk.

IX. Knowing The Limits

As with every analytical tool, its limitations must first be understood to prevent invalid results. This tool is no exception and has a number of limitations.

First, the statistical model from which the model was constructed must be understood. The formulas are presented in the paper. The model is quite simple. Components are either connected in series, or redundant and repairable components are connected in parallel. Textbooks that deal in reliability will present many connection schemes beyond these two options. However, as these different options are added, it becomes difficult if not impossible to build them into a relatively simple PC modeling technique. What this translates into in the real world is that the model will not automatically handle complex systems that have sophisticated relays and monitoring systems that automatically detect system failures and reconfigure the system to meet the requirements.

One of the first significant limitations of the model is how to deal with double ended substations that have normally closed tie breakers. It is easy to create the model but the spread sheet will result in circular references, meaning that the reliability of one bus is a function of the other and vice-versa. Using iteration techniques available within the spreadsheet program will result in failure rates for some points going to infinity. To handle this common configuration, an approximate modeling technique was devised to cover the situation.

Another limitation of the model is that it does not automatically deal with normally open redundant sources of power such as normally open tie breakers. However, by understanding the modeling technique, it can be handled by modifying the MTTR of the normal **source** to the system with whatever time is required to close the tie breaker or alternate source of power. While this will not impact the number of times the system fails, it can have a significant impact on how long it takes to restore power and therefore have a significant impact on the risk associated with each event.

The model does not deal with the analysis of hidden failures. For example, the model will not provide much insight into how many protective relays in a system will not function when called upon to do so. Statistical analysis of relay calibration data may help with this analysis but this model won't.

Probably the most significant limitation that this model has is the failure and repair data listed in the RAM Table. The output of the model will be no better than the quality of this data as it applies to the system that is being analyzed. The old saying of garbage in - garbage out certainly applies to this model. It is very critical in analyzing the results from this model to assure that it represents that actual performance of the facility.

X. Conclusion

Petroleum manufacturers are keying their business success on the quality of the products they manufacture, not on the reliability of their electrical hardware. Yet, it may become quite difficult in large single train process units to manufacture these quality products if the electrical systems do not perform well. Most suppliers of electrical equipment presently provide safe equipment to meet the customer’s demand. There is a need to understand how well components and systems meet requirements before instructing electrical equipment suppliers to focus specifically on reliability and maintainability. Users need to place a greater emphasis on how well electrical equipment should function and less effort and emphasis on how manufacturers should build it. As more users become aware of the cost impact of electrical equipment failure on their company’s “bottom line”, they will learn to define electrical reliability and repairability in measurable terms.

As outlined in Appendix 1, the software spreadsheet is being made available as freeware. It is hoped that this will encourage others to continue the pursuit of electrical system reliability in petrochemical facilities.

References

[1] IEEE Std 493-1990, "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems". (The Gold Book)

[2] J.R. Dunki-Jacobs, "An Argument and Procedure for Conceptual Power System Design Studies," in *Conf. Rec. 1993 39th Annual Petroleum and Chemical Industry Conference*, pp. 1 - 10.

[3] D. J. Smith, *Reliability Maintainability and Risk*. Butterworth-Heinemann Ltd. 1993.

[4] R. Billinton, R. N. Allan, L. Salvaderi, *Applied Reliability Assessment In Electric Power Systems.* IEEE Press 1991.

APPENDIX 1

Within the limitations stated below and additional limitations supplied with the software, Shell Oil Co. will provide the model spreadsheet as freeware. Anyone wishing to obtain a copy of the software should send a **stamped self-addressed computer disk mailer and a 3.5” high density floppy disk** to the author at the following address: John Propst, Shell Development Co., P.O. Box 1380, Houston, TX 77251-1380

The model was created to run on an IBM (TM) compatible PC, using the Microsoft Excel Version 5.0 (TM) spreadsheet program. Accompanying text files are Microsoft Word for Windows Version 6.0 (TM). The model spreadsheets and text files are copyright-reserved free programs. You may use, copy and distribute this software free of charge under the conditions supplied with the software.