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B1 Insulated Cables
PS1 Learning from Experience

Application of Fault Tree Analysis to Underground Cable Accessories

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SUMMARY

It is a common practice at many utilities to analyze failed underground distribution materials and equipment in order to learn how to reduce failure rates and improve system reliability. While certain failure modes are straightforward, others are more complex and may stem from a combination of causal factors. Furthermore, determining effective and economically appropriate preventive measures can be a challenge, especially where it is desirable for one maintenance action to address multiple root causes of failures.

The Company has been investigating the use of Fault Tree Analysis (FTA) to apply to cable accessories on the 15kv distribution system. By understanding the failure modes of cable accessories, risk on the system can be reduced and reliability can be increased. The lessons learned from the FTA are to be incorporated in our material and construction standards, Construction and Maintenance employee training, and feedback to manufacturers. These continuous learnings will further the system reliability and mature the understanding of failure modes across our underground cable system.

Fault Tree Analysis (FTA) assigns probabilities to certain initiating events, called basic events. It then combines these basic events using a series of logic gates (AND, OR, NOR, and so on), representing the consequences of different combinations of different events. These combinations are associated with simple mathematical functions for combining the probabilities of their inputs to produce a combined probability of the output. By this means, the probabilities of different combinations of a group of independent events can be computed and analyzed.

Application of fault tree methods to the problems of cable fault diagnostics allows the causes of failures to be identified and tracked at a very fine level of detail. For example, rather than categorizing a group of failures as “Workmanship Errors,” they can be detailed further as a failure of some specific operation or task. This helps to focus the preventive and corrective measures, improving their efficacy while reducing their resource requirements.

The analysis and visualization of defects and their causes is greatly simplified by the application of fault tree methods. They also make it possible to analyze different corrective

measures during the planning stage and to evaluate their effects on the failure modes that have been observed in the field.

To begin the development of a system of fault tree analysis, we built a fault tree to cover heat-shrinkable cable joints. Failure of these joints had been observed as a leading cause of network faults. Failure reports from the past year were then encoded to map them onto the fault tree until the root causes were identified. This data set was then processed to convert the observed count of failures into a relative probability figure, which was then returned to the fault tree and used to compute the probabilities of intermediate causes between the root causes and the failure itself. From this data set, some clear trends could be seen. Moisture contamination of the paper insulation on transition joints to extruded-insulation cables was a leading cause, followed by misapplication of heat-shrink components. This information implies several corrective measures that can be taken to identify and correct other potentially failing components before they produce network faults and service interruptions.

We have automated a part of the existing failure analysis database both to use the fault tree to define the chain of events associated with each failure and to collect and compute statistical data on observed root causes to feed back into the fault tree. By this method, the failures observed in the field can be used to calculate the relative importance of each branch of the fault tree directly, providing helpful information to the reliability engineers on where countermeasures can be most effectively applied to prevent network faults.

KEYWORDS

Reliability, fault tree analysis, insulated cable, trifurcating joint

1. INTRODUCTION

A problem to be solved by all electricity distribution companies (EDCs) is that of identifying the most effective use of their resources to improve the quality and reliability of service to their customers. Customers, investors, regulatory agencies, and government officials all rightly recognize this as the core duty of an EDC. Solving this problem has largely been left to professional discretion of the EDC's engineers, who often rely upon interruption reports as their chief, if not only, signal of where problems exist. This combination of expertise and good reporting has generally been adequate for the job, if not necessarily optimal.

The supply of experienced engineers has dwindled over the past few years, and may be expected to continue dwindling as an aging workforce retires and is replaced by a workforce with broader interests and greater career mobility [1]. This, plus the increasing social demand for better reliability at lower cost, has increased pressure on the reliability engineer to get a more precise, objective, reliable source of information about what is breaking down on the system and, consequently, where preventive measures will be most useful. Adding to the challenge is the increasing complexity of the power system. With the recent increase in both distributed generation and in automation of the distribution system, the diagnosis and prevention of failures becomes ever more complex as well.

The development of more advanced methods for testing equipment and components in service has compensated for some of these challenges. To the extent these methods are able to prove, rather than guess, that a component is deteriorated or about to fail, they are indeed quite helpful. However, great amounts of time and money can be consumed by testing at random, and some sort of testing strategy is usually needed to ensure that tests are focused on areas of known or expected trouble. It is also more economical and effective to identify and use tests that are focused on specific expected failure modes than to use generic tests that may, or may not, identify conditions of actual concern.

It is in this context that the Company has been investigating more advanced methods of failure analysis to apply to its distribution system. Many such methods exist and have been applied to areas where reliability is especially critical, such as in aviation and nuclear power generation. The method that we have chosen to apply is Fault Tree Analysis (FTA). While the intent is to apply FTA across the distribution system, the initial test application has been made to certain underground cable accessories that had presented an especially high rate of failure.

2. PRINCIPLES OF FAULT TREE ANALYSIS

FTA assigns probabilities to certain initiating events, called *basic events*, or in some implementations, "root causes." These represent the independent conditions that, in the right combinations or under the right circumstances, can lead to some undesired outcome. A probability can be assigned to each of these basic events.

The basic events can then be combined to reach an intermediate event or condition, and in FTA, this is represented by logic gates (AND, OR, NOR, and so on), representing logical combinations of certain inputs to produce a specific output. We may say, for example, that intermediate condition X will only result if input conditions A and B both occur simultaneously; we can represent this as a logical AND gate. Similarly, if we say that intermediate condition Y occurs if input conditions C or D occur, or both of them, we can represent this as a logical OR gate.

The aggregate probability of an outcome given the probabilities of the inputs can be computed by simple mathematical functions associated with the logical combination of the inputs. The probability of X, in the example above, is the algebraic product of the probabilities of conditions A and B. Likewise, the probability of Y is approximately the sum of the probabilities of C and D, minus the probability of C and D occurring simultaneously. Therefore, if we know the probabilities of the basic events, we can compute the probabilities of each intermediate outcome that is linked to those basic events. Likewise, intermediate outcomes may themselves be connected by logical gates to other intermediate outcomes, and so on until some undesired outcome is reached. The probability of each intermediate outcome, together with the final undesired outcome, can be computed in this way [2].

An example may help to illustrate the concept. Say, for example, that the outcome we wish to analyse is the failure of a car to start. This may have a number of causes: lack of fuel, a dead battery, several kinds of mechanical breakdowns, and so on. If we examine the dead battery condition, this itself may have several causes: exhaustion of the battery chemistry, failure of the charging system, some load left on to discharge the battery, and others. Moving on to the discharged battery, this too may have causes, among which could be a failure to switch off the headlamps after parking. Thus far, we can trace a causal chain from failure to start back to a more specific cause: the engine will not start, because the battery is dead, because the lights were left on.

What is especially useful about FTA is that it is able to combine causal factors in different ways using relatively simple logic. Thus, we may examine the problem of the lights being left on, and determine that this is the combination of two problems: on the one hand, that the lights were switched on and forgotten, and on the other, that the alarm indicating the lights had been forgotten failed to operate (which itself may have causal factors). The resulting chain of events may then be diagrammed as shown in Figure 1.

While this is a simple example, the principles may easily be applied to much more complex systems. The granular breaking-up of a system failure model into a number of small, discrete, connected events allows even highly complex systems to be analysed in great detail and with good accuracy. Since FTA is able to compute the probability of different intermediate events, it is able to identify which chains of events present the greatest risk of causing the ultimate undesired event. From this, the appropriate point at which to introduce preventive measures can be identified and its effect estimated. Continuing our example above, suppose that we determine the risk presented by this chain is too high. We might find that the most appropriate point to introduce a countermeasure is above the failure to turn off the headlamps before parking, perhaps because this is a point with a high probability of occurrence, or perhaps because a preventive measure can be introduced with greater efficiency than elsewhere. We could, for example, install a reflector on the wall facing the headlamps at the parking space. This can be modelled in with an AND gate, as illustrated in Figure 2: the outcome of failing to turn off the headlamps on one input, and the outcome of failure to notice the light of the reflector on the other (illustrating, of course, that no preventive measure is immune to failures of its own). It is then possible to compute the probability of the car's failing to start with this measure in place and see whether it is reduced enough to justify the cost of the measure.

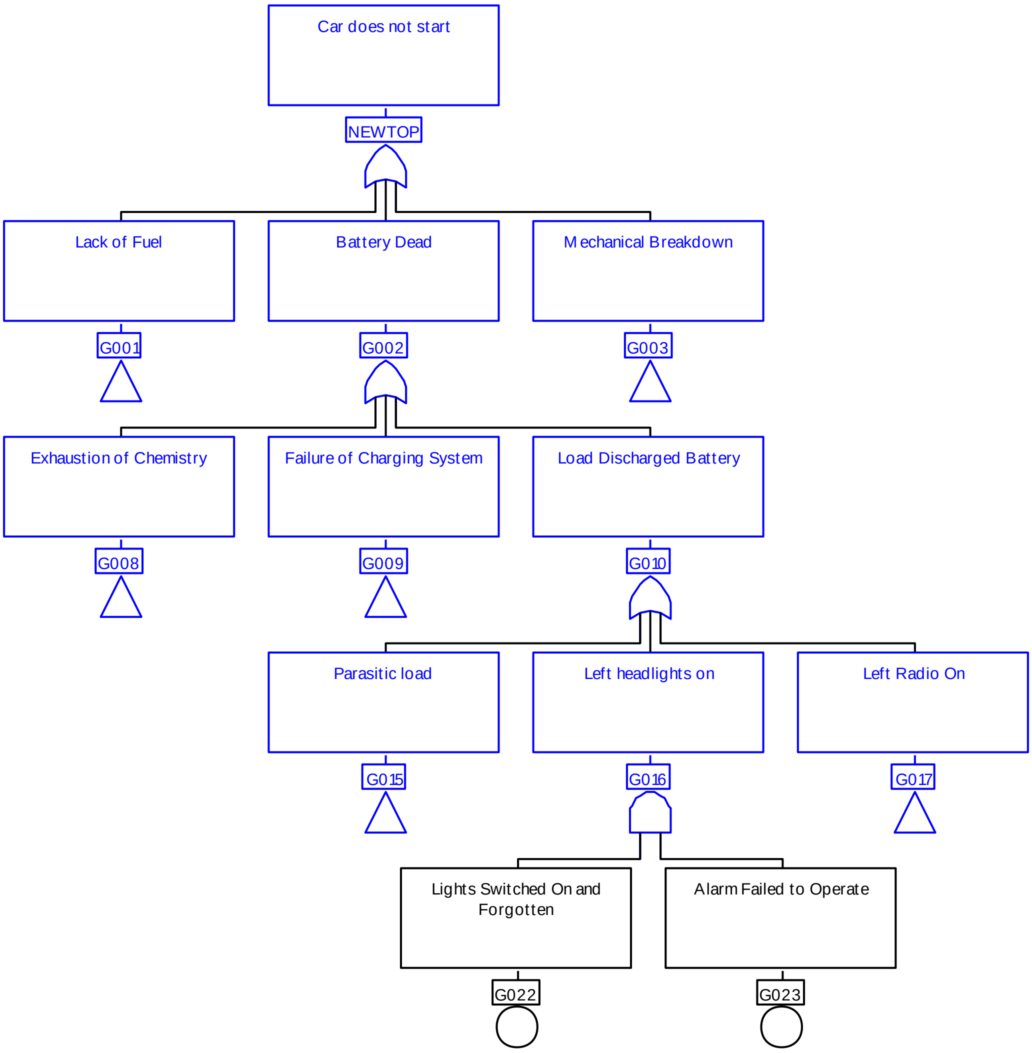

Figure 1: A fault tree for a car that will not start.

3. APPLICATION TO THE POWER SYSTEM

When applying FTA to the power grid, the initial system model can be relatively simple: in most cases, OR gates are sufficient. For example: a power cable fails if the insulation fails, or the phase conductor fails to conduct, or the sheath fails to conduct, and so on. Each of these can often be traced to some OR combination of causal factors: the insulation fails to insulate when it is mechanically damaged, or when it becomes wet, or when it becomes overstressed, and so on. The use of AND gates is largely limited to modelling preventive measures, as illustrated in the example above. Thus, we may indicate that cable insulation failed due to some combination of causes, AND the failure of cable testing to detect weakened insulation. It is entirely possible to model more complex interactions of causal factors, but it is not usually necessary for the purpose of power system reliability when the point of interest is determining the failure rates and mechanisms of individual components. However, if there is a desire to

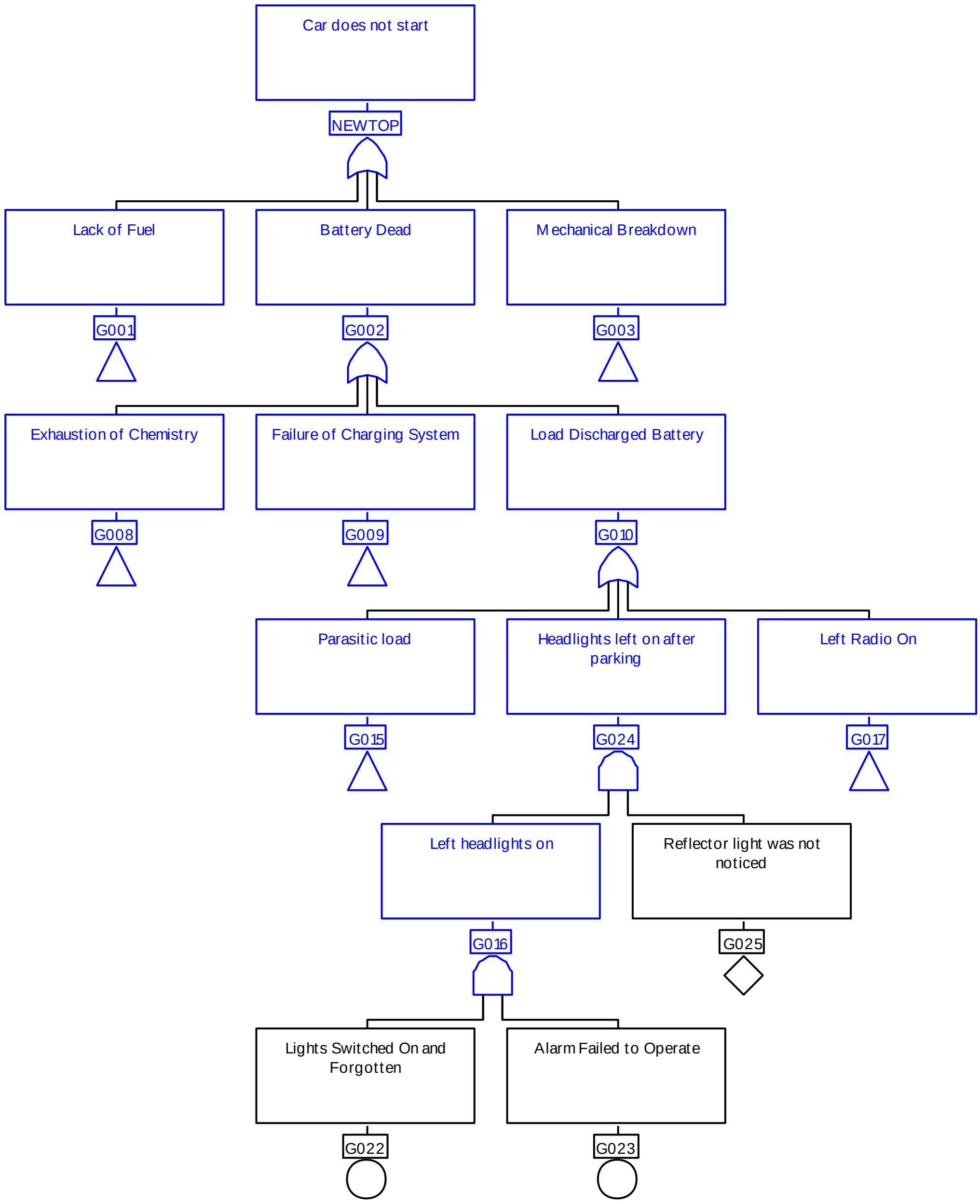

Figure 2: Fault tree for a car that will not start, with a countermeasure modelled (at G024)

model the failure of some non-critical components (such as radios) and their interaction with other more-critical components (such as radio-controlled switches), FTA is more than capable of handling this.

For determination of component reliability, it is appropriate to structure the fault tree so that the undesired outcome is failure of that component. The inputs to that outcome may then be described as the various *modes* of failure: failure of insulation, failure of conduction, and so on as appropriate to the kind of material. Each of these modes has a set of causes, each of which may itself have causes, and so it goes as the tree branches out until the basic events—the conditions that do not have specific traceable causes themselves—are reached. Part of an actual fault tree that follows this model is shown in Figure 3.

Developing a fault tree after this model allows the causes of failures to be identified and tracked at a very fine level of detail. Firstly, the tree itself provides a map for analysing equipment failures. Starting from the failure of a piece of equipment, the mode by which it failed can be identified by examination. Then an appropriate cause of that mode can be selected from the tree, and then a cause for that cause. Where the cause is not obvious, the tree provides a limited selection of possible causes to consider, guiding the analyst to select appropriate analytical tools or methods. Eventually an appropriate basic event is reached. The path traced through the fault tree thus describes the chain of events involved in the failure.

Secondly, once a fault has been diagnosed and described in this way, it is possible to count the number of basic events that are identified in a certain time period and to use this number to estimate the incidence of basic events on the system as a whole. If there are 10 000 of a certain kind of equipment on the system and, on average, basic event G is found once per month, this implies a probability of G of 1/10 000 per month. This quantity can then be applied to a completed fault tree to compute the probabilities of each intermediate condition. From this, the most significant intermediate conditions can be identified, and preventive measures targeted to those, gaining both more efficiency of action and more certainty of effect.

Once the basic structure of failure modes has been defined in this way, and the incidence of defects has been computed, it becomes possible to determine by examination which points on the fault tree will have an especially high influence on the number of system failures. Then, preventive measures can be selected and applied at those points, and the effect of those measures computed and predicted based on the observed incidence of the various basic events. Thus, for example, a test routine can be selected and applied to identify an intermediate condition of special interest when it occurs on the system, representing some group of basic events and their interactions with one another. This test routine can be directly modelled in the fault tree and a probability of success assigned to it, which can then be accounted for in the calculation of failure probabilities.

The statistical calculations at each stage are simple enough, and the logical combinations of different probabilities can be done, step-by-step, through a very complex system using FTA as a guide. Applying FTA to a distribution system holds enough promise for bringing to light what is in need of attention, and to what extent and at what level of priority, that a test implementation was done on the Company's system to determine its effectiveness and its potential for reliability analysis.

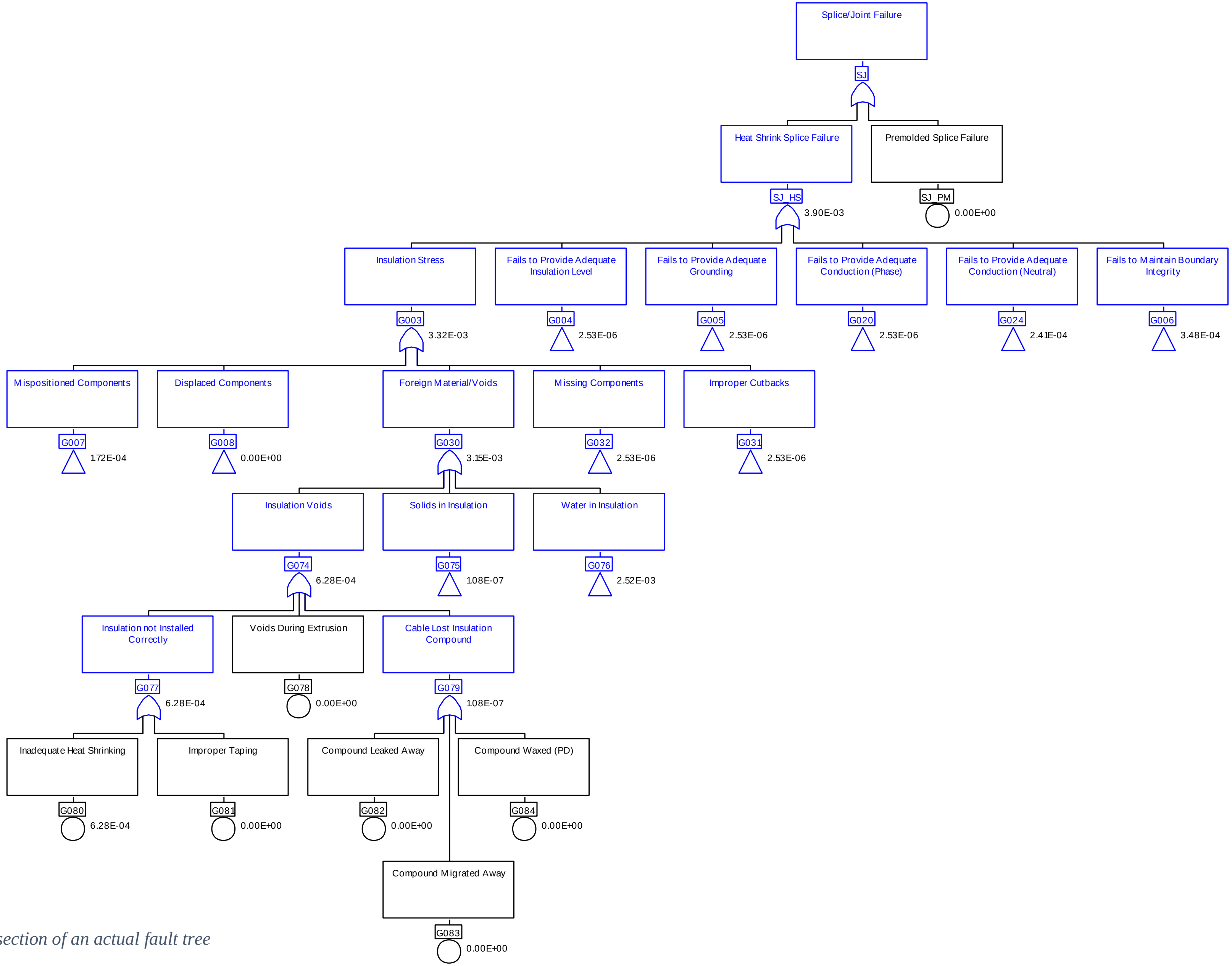

Figure 3: A section of an actual fault tree

4. TESTS AND FINDINGS ON THE COMPANY'S SYSTEM

The initial implementation was designed to describe failures on heat-shrinkable cable joints. These kind of joints have been responsible for a majority of underground network faults, leading to a heightened desire for precise information about the causes of these failures. A section of the fault tree that was developed is shown in Figure 3. The tree as developed describes the major modes and causes of failure for this type of joint. It is important to note that, during tree development, no attempt was made to quantify the likelihood of any branch of the tree. The process at that stage is to identify and describe all plausible failures based on the characteristics of the material itself. In this way, it is possible to design a fault tree without having any data on the actual causes of failure being experienced, and it is even possible to design a fault tree before equipment is installed.

Once the fault tree was designed, a set of 42 failure reports involving heat-shrink cable joints for the past year were reviewed and encoded to map the individual failures into the fault tree, and where possible a basic event was identified for each failure. In some cases, multiple independent basic events were identified for the same failure. This is normal and expected, and the fault tree methodology allows these failures to be counted once under each basic event so that a more accurate measure of defect incidence can be obtained.

Having coded the reports in this way, the resulting data set was processed to scale the observed count of failures into a relative probability. The premise of this operation follows: supposing that the total population of a class of equipment on the system is z. Of this population, a total of y units fail in a given month from all causes. Of these, a units failed with a certain root cause A. We desire to determine the ratio of a to z, which is the rate at which root cause A appears within the population.

Of the population on the system, a total of x units are submitted for more detailed laboratory examination such that a full fault tree analysis can be performed and data recorded. Of these, there are a' units that are found to have root cause A. Assuming that x is a representative random sample of y, we can assume that

$$\frac{a'}{x} = \frac{a}{y} \qquad [1]$$

Or in other words, that the rate at which a certain basic event is observed in the laboratory sample is equal to the rate of that event's occurrence across all failures. By some rearrangement, this can be made to show that

$$\frac{a}{z} = \frac{a'y}{zx} \qquad [2]$$

so that the rate at which cause A appears in the population can be calculated from known quantities. Using this relation, we are able to convert the observed number of defects from each basic event into an estimate of incidence of that defect across the population. Repeating this calculation for each observed basic event produces a set of estimated probabilities for them that can be put back into the fault tree and used to calculate the probabilities of the intermediate events, which is done by the method described previously.

One danger of this method is that, on many systems, the incidence of failure relative to the installed population is quite low. It is necessary to generalise from the few failures that occur and are analysed thoroughly to the performance of the entire system. In the extreme case, this can mean, for example, that a single equipment failure is generalised to represent performance of the whole system and may seem to indicate that there is only one kind of failure to be concerned with. It is necessary to repeat this exercise for enough periods to determine an average performance before relying too heavily on the result. For this experiment, twelve months of data were analysed and averaged to obtain an average result. While this may not be enough to get a high level of statistical confidence, the level of confidence is high enough that the results are usable for engineering.

This process produced the results shown in Table 1. By far, the greatest number of failures were the result of water being in the cable (usually, in this case, a paper-insulated cable) before the splice was installed, followed by inadequacy of the heat shrinking. Mispositioning of the various components made up many of the other defects observed.

One benefit of this level of detail is the ability to specify more clearly just where the problem lies with this component. Under the current scheme used to classify outages, all of these would have been classified simply as “Underground Fault,” and under the scheme used to classify lab investigations, almost all would have been reported as “Workmanship Defect.” Neither scheme is especially helpful to correcting the problem, however: knowing it is a fault in underground equipment says little about the cause, and while knowing it is workmanship is slightly more helpful, it does not indicate where improvements are needed. Knowing, in this case, that the chief trouble lies in the presence of water in the cable before splicing suggests that any corrective measures should address exactly that issue, whether that means improved techniques for detecting water, better adherence to inspection practices, or something else.

Table 1: Observed failure probabilities

Cause	Probability (x 1×10^{-5})
Water in Cable Before Splicing	235
Inadequate Heat Shrinking	62.8
Mastic Out of Position	34.4
Stress Control Layer/Tube Mispositioned	17.2
Water Migrated to Joint	17.2
Excessive Mastic Used	17.2
Wrong Placement	6.78

5. FURTHER DEVELOPMENT

The last issue mentioned above suggests another area of improvement in data collection and analysis practices. The use of different code schemes for fault reporting and for defect investigation hampers the efficient use of field information for reliability improvement. The challenge to this point has been that each set of codes has had distinct requirements. The field reporting codes normally focus on general observations such as can be made in the course of fault repair. This causes them to focus on immediately-observable characteristics of the fault rather than on root causes. Fault investigation, on the other hand, presumes both the ability to conduct an in-depth investigation and the need to report conclusions about the causes of failure.

The FTA system provides some means to bridge this gap. Since FTA describes a sequence of individual conditions, it is possible to describe a fault by using only a part of the tree. While this may not reach a basic event (root cause), it does narrow down the field of possibilities for subsequent investigators and provides crucial clues to what has happened. It is also feasible to include “partial trees” (those that do not reach a root cause) in the calculation of probabilities, although in the test case described here this was not done due to limitations of the analysis software. By doing this, field intelligence regarding fault conditions can be incorporated directly into the analysis without requiring full-depth investigations during fault repairs and without requiring translation or conversion from one coding scheme to another.

The further development of this project is planned to include expansion of the FTA system to all kinds of materials used in power distribution. It is also planned to begin field reporting of faults using the top two levels of the fault trees so that later investigations can be more easily connected back to the field report, or where later analysis contradicts the field report, to more easily identify the right coding.

No plans are in place to model preventive measures in the fault tree at this time, largely because the effectiveness of those measures is not precisely known at this point. However, the model is fully capable of integrating and evaluating those measures when it is desired to do so. The benefits of modelling preventive measures, and the ability to estimate more reliably the benefits of those measures, present some exciting opportunities for the reliability engineers and project planners.

6. CONCLUSION

Fault tree analysis holds much promise for simplifying the analysis of failed material while still providing excellent detail of the causes of outages. A limited number of investigations can be extended to describe the state of the system in general, reducing the time and expense of failure investigation without substantially degrading the quality or usefulness of the results.

When applied to underground materials, FTA is especially effective at detailing the causes of failures and directing resources toward appropriate preventive measures. Very precise causal factors can be stated, but these can also be grouped together under higher-level intermediate causes to indicate points at which a single preventive measure can be taken instead of diffusing resources across multiple root causes that have lower individual significance.

The efficient determination of failure causes and appropriate preventive measures, including changes to engineering standards and practices, is especially important in the current EDC environment. Serving the demand for increased reliability with the limited resources available is made more practical when the causes of failure and their solution can be determined rapidly and systematically using methods such as FTA.

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