Using Root-Cause Analysis to Find Underlying Causes of Bad Outcomes

Root-cause analysis, often called RCA, is a way of thinking about how to fix problems. By understanding the concept of finding underlying causes of problems, testing engineers have the technical knowledge and experience to become experts in root-cause analysis.

As testing engineers, we often conduct forensic investigations to identify the direct causes of bad electrical events, but I doubt that more than a few of us have been requested to identify the underlying issues that led up to that event. NETA companies can add this skill to their marketing brochures by understanding what RCA is and how it should be conducted. Although several companies offer week-long RCA seminars, I found that engineers can sufficiently understand and apply RCA principles within a few hours by following the seven rather simple steps discussed in this article.

NETA companies are often called to help conduct investigations following a bad electrical event. Here is another opportunity to provide “lagniappe,” (a Louisiana French word pronounced “lan-yap”), meaning to give the customer something more than expected. You can offer to your client, in addition to conducting a forensic investigation of the event, to also conduct a formal root-cause analysis of the event. The selling point is that the customer will find out what are the underlying causes of a bad electric event. He can then implement effective procedures to fix the problems.

What is root-cause analysis?

RCA is often thought to be the simple investigation of what caused something to fail. It actually is the formal process of delving through, identifying, and sorting out the layers of causes and conditions that led up to something going wrong - the undesired event. RCA requires asking the question, why did that happen?, for each layer of causes, as many times as necessary to identify all conditions and causes leading to the undesired event, including finding the most underlying root causes of the event.

Root-cause methods vary, but I found the following method to be rather simple and effective.

Step 1: Conduct a forensic investigation.

The forensic investigation identifies equipment damages and personnel injuries resulting from an event, it identifies the timeline of actions leading up to the event, it identifies the direct causes of the damages and injuries, and it identifies possible contributing conditions. This often requires interviewing witnesses and experts, inspecting physical evidence, reviewing records, and conducting laboratory tests. The forensic investigation primarily determines what happened, and the immediate causes of why did that happen?. The forensic investigation generally identifies some direct causes but not the less obvious hidden causes, including the most underlying root causes. Often investigators stop analyzing an event at the conclusion of the forensic investigation, resulting in no solutions other than blaming the event on the equipment manufacturer, or on worker error, or resulting in solutions that do not fix the underlying causes. This can lead to the recurrence of the bad event or to similar events. Forensic investigations are often reopened during an RCA to confirm hypotheses generated by the root-cause analysis process.

Step 2: Determine the need for, and select an RCA team.

Because full-blown investigations and RCAs can be expensive, some companies limit formal forensic investigations and root-cause analyses to major injury-causing and big dollar events. Forensic investigations and the follow-up root-cause analyses should always be conducted following any bad electrical event, even a minor event – to minimize the chance of similar, but more catastrophic, follow-up events.
RCA investigations for minor events can be conducted, usually at minimal costs, by one or two experts. However, a team of experts generally is necessary to conduct the forensic investigations and RCAs of complex events that need multiple experts or for those events that had catastrophic results, i.e., injuries, death, or large financial losses. To prevent compromised conclusions, the team of experts should be led by an RCA expert who does not have a direct or an indirect interest in the RCA outcome. Sometimes, RCAs fail to identify true root causes to prevent embarrassing management personnel.

**Step 3: Identify the event’s undesired outcomes.**

One event could have several undesired outcomes. For example, an electrical event at an oil pumping station might have resulted in financial losses, injury, pollution, and legal penalties. RCAs should be conducted separately for each undesired outcome.

**Step 4: Develop hypotheses. Prove or disprove cause and contributing condition hypotheses.**

The purpose of developing hypotheses is to identify possible direct causes, intermediate causes, and contributing conditions not identified in the forensic investigation. Hypotheses are theories, opinions, premises, suggestions, suppositions, propositions, guesses, assumptions, or the postulations that identify possible causes of an undesired outcome. Using timelines and evidence uncovered from the forensic investigation, and starting from each undesired outcome going backwards to the root causes, the RCA expert or team should hypothesize what could have happened? and why did that happen? until the questions cannot be further answered. Some what could have happened? hypotheses are identified by the forensic investigation, but some possible, but unlikely, outside-the-box hypotheses should also be identified, i.e., criminal action, freak weather, incorrect parts, etc. It is important that all hypotheses, no matter how unlikely, are considered before proved or disproved by factual evidence or by expert knowledge. Not considering less obvious hypotheses might lead to erroneous conclusions. Also, more than one train of causes and conditions could exist, leading up from more than one root cause, to the same undesired outcome.

**Step 5: Identify and sort causes and make cause-and-effect trains.**

Once hypotheses are proven or discarded as either non-factual or not related to the undesired outcome, the expert or team should sort the proven hypotheses into cause-and-effect trains using the logic described as follows.

- **Direct Causes** - i.e., equipment manufacturing mistake and worker error – are correctable events that most directly resulted in the undesired outcome. There may be more than one direct cause. The most common RCA mistake is identifying the most direct causes as root causes.
- **Intermediate Causes** – i.e. improper training and excessive working hours - are correctable events that lead to the direct causes or to other intermediate causes. Not all RCAs have intermediate causes.
- **Contributing Conditions** - i.e., weather, equipment design, and equipment age – are conditions, which if they had not been present, a direct cause might not have resulted in the undesired outcome. Contributing factors do not cause the undesired outcomes and are not usually correctable. However, sometimes contributing factors can be changed or controlled to some extent to reduce the chance of recurrence, or to reduce the severity of the outcome. Understanding contributing conditions helps determine if solutions will be adequate.
- **Root Causes** - i.e., inadequate procedures, taking unnecessary risks, and using lowest cost equipment – are the most underlying conditions, actions, or inactions that led to the intermediate or direct causes, which eventually resulted in the undesired outcome. Root causes are usually management decisions made, or that should have been made, that would have prevented the intermediate and direct causes of the undesired outcome. Conversely, the RCA might prove that the past management decisions were adequate and were not the root cause of the undesired outcome.

**Step 6: Develop Solutions**

The RCA is not complete until How can that be prevented? is identified and evaluated for each direct, intermediate, and root cause. If a cause does not have a solution, or a reasonable cost-benefit, then that cause should be changed to a contributing condition. The team must determine how, by applying the other solutions, the recurrence of the undesired outcome will be prevented. Others, outside of the RCA team, should review the RCA report and should be requested to question the hypotheses and conclusions. Sometimes, comments from nonelectrical people for electrical RCAs provide valuable insight, and they should always be considered.

**Step 7: Solutions Follow-Ups**

The RCA does little good unless the solutions developed are implemented. Not implementing a solution might be the root cause of a subsequent undesired outcome. Part of the root-cause analysis procedures should be to assign someone the responsibility for implementing the solutions and to assign someone else the responsibility for verifying that the solutions were implemented and completed.
Example Case:

A Substation Basement Fire

At an electric utility, a substation control and switchgear building containing about 30 medium-voltage circuit breakers, the station battery, and other equipment also contained a confined-space basement located under the main floor. The medium-voltage power cables, control cables, and battery leads were all located together in the basement, just below the switchgear. One of the power cables in the basement faulted resulting in an arc-fed fire which consumed other power cables, relay and control cables, and the battery leads. The fire progressed to the main floor via openings in the floor and destroyed the station battery and damaged switchgear components. Although one circuit breaker tripped, others did not because dc power was lost due to the fire, early in the event. Dispatchers could not remotely operate any of the circuit breakers and the substation was not de-energized until transmission circuit breakers were opened at other substations. The fire consumed nearly all equipment in the basement and some of the equipment on the main floor. The undesired outcomes were (1) the failure of a cable splice, (2) millions of dollars in equipment losses, and (3) the extended loss of service to some customers.

A forensic investigation was conducted for the first two undesired outcomes. A lessons-learned evaluation was conducted for the third undesired outcome. The forensic investigation team was led by a qualified relay engineer and a consultant with expertise in substation fire investigations. The team interviewed the utility employees and fire fighters that responded to the fire. Timelines were developed indicating the fire propagation, operator and dispatcher responses, and customer restoration procedures. The team concluded that the fire started when a cable splice failed and that action to open circuit breakers remotely to prevent feeding the fire was not done because the dispatcher had ignored the substation fire alarm indicator.

The team retained other experts to inspect and test the splice and determined that aluminum connector in the splice had not been annealed and that it had not been properly crimped onto the cable conductors. The team concluded that the connector had overheated when excessive load was placed on the cable, eventually causing the arcing fault that started the fire. They purposely faulted an energized cable splice in a laboratory and proved that the splice jacket material would be set afire by a fault at the splice. They also purposely shorted the leads on a station battery and determined that the battery did not contribute to the propagation of the fire when its leads were shorted by the fire in the basement.

An RCA team was formed which included equipment and protection engineers. A consultant was asked to participate.

1st Undesired Outcome:
The failure of the cable splice

The Direct Cause
• Installer’s error – the installer crimped the connector properly but failed to recognize that the connector was not annealed (it was too hard).

The Contributing Condition
• Manufacturer’s error – the connector had not been annealed. The owner could not have done anything to prevent this. The owner knew that it had some bad connectors but did not know where they had been installed. The manufacturer had already corrected its manufacturing error. Many investigators might conclude that this was the root cause and no solutions would then be developed.

The Intermediate Causes
• Dispatcher and maintenance errors – the cable had been loaded in excess of its normal rating for weeks prior to the fault. The load from another circuit had been transferred to this cable, while the other circuit was being repaired. The repair of the other circuit had not been expedited. However, overloading would not, by itself, have caused the cable to fail.

The Root Causes
• The owner’s cable splicer training was inadequate.
• The owner did not have a splice assembly quality control program in place.
• The owner had no formal procedures to minimize cable overloading.

The Solutions
Solutions should be developed for direct, intermediate, and root causes, and possibly for contributing conditions.

The owner
• improved and intensified its cable splicer training program and its cable splice quality control procedures.
• implemented a formal program to limit overloading of cables.
• implemented periodic and ad hoc programs to infrared inspect cable splices located in substation basements.
• stopped installing new cable splices in substation basements.

These solutions were implemented and no subsequent cable splice faults have occurred in substations with basements.
2nd Undesired Outcome:
Equipment losses

The Direct Cause
• The fire which consumed equipment in the control building basement and on part of the main floor.

The Contributing Condition
• The placement of control cables with power cables in a confined space.

The Intermediate Causes
• The lack of fire protection for the control cables and other equipment
• Openings between the basement and the main floor allowed the fire to propagate to the main floor switchgear and the battery.
• The dispatchers in the control center ignored the fire alarm which delayed the immediate response to the fire. The dispatcher could have de-energized the substation before the control cables burned.

The Root Causes
• The root cause was the owner’s failure to provide funding to take fire prevention measures as recommended by its engineers following prior substation basement fires.

The Solutions
• The owner developed a substation fire protection group dedicated to identifying the best practices to prevent the propagation of fires in substation basements.
• The owner implemented and funded a substation basement fire protection enhancement program including wrapping cable splices and control cables in basements with fire resistant material, filling the openings between the basement and the main floor, moving battery cables from the basement, and in some cases installing fire suppression systems.
• The owner installed improved fire detection systems and improved the SCADA fire alarm system at the dispatcher desks. Because the improved fire alarm systems still allowed an excessive number of false alarms, no procedure was put into place for dispatchers to drop substations because of fire alarms. It was determined that the implementation of substation basement fire protection enhancements would prevent fires in basements. Therefore, dropping loads via SCADA before an operator arrived, based on suspect fire alarms, was unnecessary.

Subsequent to installing fire protection enhancements, the owner experienced at least two cable faults (not splice faults) in substations with basements. The fire protection enhancements prevented resulting fires from propagating to other equipment.

3rd Undesired Outcome:
Not restoring some customers until the substation was partially restored, several days after the fire

The owner had formal restoration teams in place to guide the restoration process. From the company’s lessons-learned follow-up process, it identified some areas where restoration of customer services, following total substation outages with extensive equipment damage, should be improved.

Outages will occur when substation equipment fails. However, extended outages should not occur, even when a substation is damaged by fire. The extended outages occurred on loads that were stranded – loads that could not be picked up by other substations. Some loads were later picked up by portable generators. However, the remaining loads were not picked up until the substation was partially re-energized, several days after the fire. The owner did not have sufficient generators available to pick up all loads.

The owner had restoration teams assigned on a 24-hour basis and had some large portable generators ready to install. However, it did not have predetermined restoration plans for actions to take when extended total substation outages occur, it had not predetermined the number generators it should have available for total outages for each substation, and it had not identified stranded circuits and generator placement locations for each substation. It had also not conducted mock restoration exercises caused by substation fires.

The restoration time for most of the affected customers was reasonable. However, some customers were not restored until the substation was partially restored, several days after the fire.

The Direct Cause
• Insufficient number of generators. The owner did not have sufficient number of portable generators readily available to pick up all stranded loads following the fire. It also had not identified generator site locations until after the substation outage began.

Contributing Conditions
• The substation fire caused the outages and the equipment damage that slowed the restoration of the stranded loads.
• It is not cost-effective, nor common, for utilities to have the facilities to be able to transfer all customer loads to other substations for a total substation outage.
• Waiting for safety and environmental authorities slowed the restoration by a few hours.
• Some stranded customers had to wait several days before their service was restored until the owner was able to move some circuits to undamaged switchgear and to safely re-energize a part of the substation.
Root Cause
• The owner was not fully prepared for an extended substation outage. Although the owner had emergency response teams in place, it had not conducted studies to identify how, and did not have sufficient resources ready, to restore all stranded customers within 24 hours.

Solutions
• The owner conducted a study to determine the amount of stranded loads for each substation and it determined emergency generator requirements, based on the study.
• The owner modified its emergency response procedures to improve its substation restoration readiness, based on its follow up lessons-learned report.
• The owner began conducting mock substation fire drills to train its dispatchers, its operators, and its emergency response teams.

Following a formal method to conduct root-cause analyses, as discussed here, allows investigators to conduct their investigations in an orderly fashion, preventing incomplete analyses, and resulting in the proper conclusions and effective solutions. Once I began to use RCA for analyzing bad outcomes for clients, I found that RCA thinking made understanding the root causes of personal and world problems much easier. Do you think that Capital Hill solved the economic meltdown problem by addressing only the direct causes? You can work that out on your own.

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