ELEMENTS OF A POWER SYSTEMS RISK ANALYSIS AND RELIABILITY STUDY

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Abstract - Risk analysis and reliability studies are essential tools for the design of continuous process plants. This paper uses examples from a producer gas manufacturing plant and an aluminum smelter to show how reliability and rate of return analysis are used to evaluate various reliability upgrade options.

INTRODUCTION

Power systems, like other utility and support systems, are often taken for granted by plant personnel as part of the infrastructure that will always be there and available on demand. Electrical engineers, however, are well aware of the level of power system reliability and the associated costs to provide that reliability. Fortunately, technical bodies have compiled statistics and published standards so that power systems can be analyzed and reliability quantified. Equipment failure is a fact of life; it will happen. Using industry-wide reliability figures and methods outlined in standards such as IEEE Standard 493 (Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems), system failure rates can be calculated. These system failure rates can be converted to risk cost to justify reliability improvements to the power system. This is investing money in a planned fashion rather than waiting for a failure to occur and then using the failure to justify the repair cost.

This analytical approach will remind plant management that there are no “fail-safe” solutions and will also prevent the engineer from overselling the results of a power system upgrade.

This paper describes two examples applied to continuous process plants. The first example shows how power system upgrades have been justified based on reducing the risk of plant power system failure. The second example shows how quantified risk identified the solution.

POWER SYSTEM FOR ALUMINUM SMELTER WATER SUPPLY

This example is for an aluminum smelter, producing aluminum ingots from alumina. About 600 MW of rectifiers convert ac to dc power for the electrochemical reaction. The major concern with a power failure to the plant is that the molten aluminum in the process will freeze in several hours after loss of dc power. The cost to restart the process can be as high as $100 million.

Apart from the reliability of the main power system to deliver power to the rectifiers, the rectifiers themselves are water cooled and any prolonged failure of the water system can cause a shutdown of the rectifiers. This example deals with the reliability consideration of the water supply.

The plant engineers are aware of their vulnerability to the water supply and the plant system already has dual 13 kV feeds to the pump houses to ensure a backup source of power. The system was originally designed with standby pumps and redundant equipment for system reliability so that failure of a single pump, motor, or switchgear component is backed up by redundant pumping systems.

The equipment, however, is a mix of vintages from the 1950s to the 1970s, causing concern for system reliability due to the age of the equipment.

Since additional pumps were added to the original system, there was also a concern as to whether the overall system reliability was properly considered with each addition. Fig. 1 shows the pumphouse electrical system one line prior to the recent upgrade.

A system reliability study was undertaken to review the electrical system for the water supply. Following IEEE Standard 493, the pumphouse electrical system was modeled using a fault-tree type analysis representing the various failure modes of the system.

This model was simplified and organized by partitioning the system into a number of “minimal cut sets” connected in series. A “minimal cut set” is an event or group of events that will independently produce an overall system failure. The components within each “minimal cut set” are in parallel, and all these components within the cut set must fail in order to cause a system failure.

Each component within the “minimal cut set” is typically an event such as transformer failure, cable failure, and other equipment or system failure. The same IEEE standard provides failure rates for these components making it possible to calculate the failure rate of each “minimal cut set”. The failure rates of all these “minimal cut sets” were then combined to form the failure rate for the overall electrical system.

System analysis is simplified by reducing the number of “minimal cut sets” to only those with components that will produce a forced down time failure greater than six hours, the time estimated for the aluminum to freeze in the process.

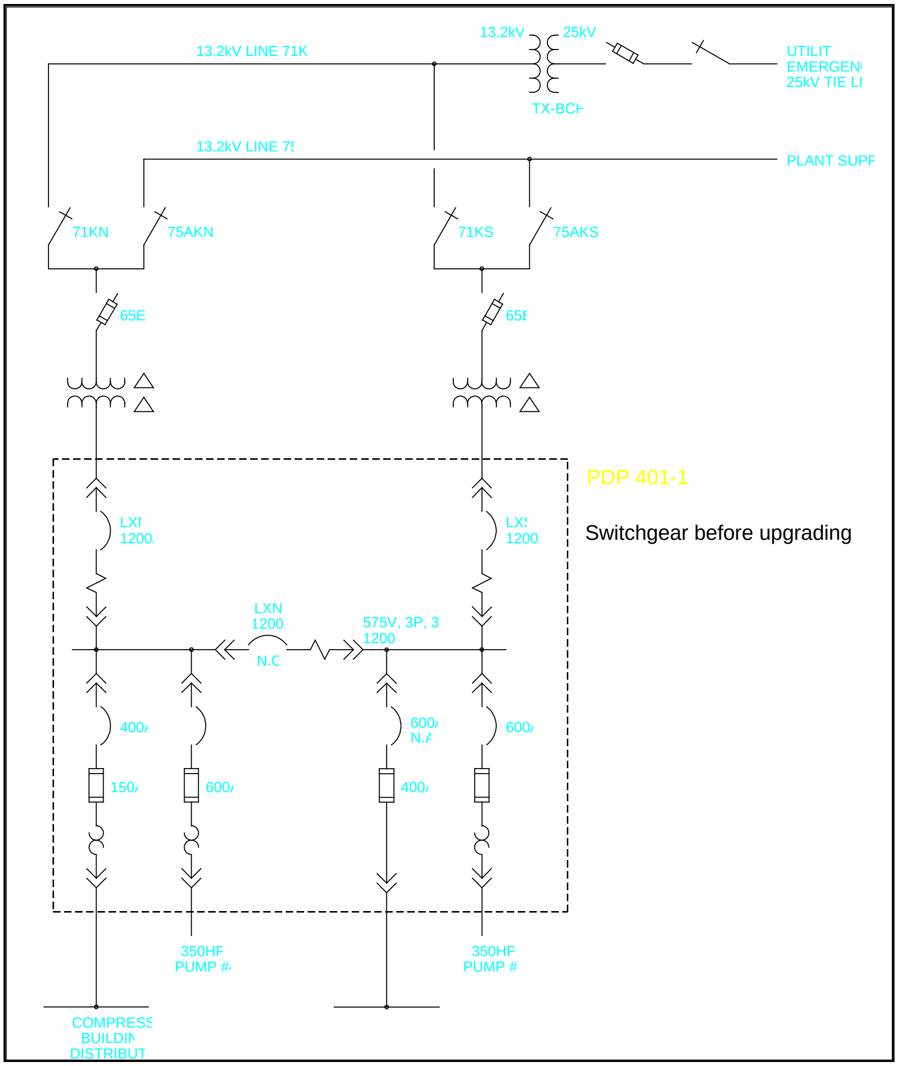

Fig. 1. Aluminum Smelter River Pumphouse Simplified One Line

Table I summarizes the probability of failure of the system for six hours. The first column refers to the failure rate calculated for each of the three electrical systems presented. These figures are then adjusted for the number of month in the year when these systems are essential to the overall water supply. The final column shows a probability of failure in 30 years to put some of the failure rate in perspective relative to civil engineering failure rates expressed for the system.

The bottom row shows the overall effect of the three systems on the pumphouse system failure rate.

The analysis is simplified because the average down time of most component failures is less than the critical six-hour duration needed to constitute a catastrophic failure. Other equipment failure combinations, such as the loss of three out of four pump motors, are also possible but have been discounted because there is a 50% redundancy level in the pumping units for the four pumps under normal water usage at both stations, and resultant failure rates become extremely small when more than one standby or redundant pumping unit failure is required to cause a pumping system catastrophe.

The study then establishes a reliability target for the electrical system by comparing it to a civil engineering water supply system risk assessment report, which cited failure ranges of between 1:100 and 1:950 over a 30-year period. There were plans to increase the civil aspects of the water supply to one order above that level. The electrical system probability of failure was then targeted for a range of 1:1,000 to 1:10,000.

The cost of recovering from a prolonged power failure was reduced to an annual risk cost based on the probability of failure. Table II shows the annual risk cost as derived from the cost of recovering from a prolonged power failure multiplied by the annual probability of power system failure.

The reduction in annual risk cost was then compared to the cost of implementing the switchgear upgrade. This translated the justification into a rate of return analysis balancing capital expenditure against reducing the risk of failure presenting a financial case that plant management is familiar with.

Two switchgear upgrade options were considered and their projected probability of failure rates calculated. Option #2 is a direct replacement of the existing aging power distribution switchgear with new switchgear and motor control centres. This is the conventional approach and replaces each existing component in kind by new devices.

Option #1 aims at reducing the components in the system. The two transformers each feed their own motor control centres and main and transfer breakers are incorporated into the motor control centres (see Fig. 2). Apart from saving equipment costs, this simpler system also increases reliability by reducing the number of devices that can fail.

The reliability benefits of the two switchgear upgrades are expressed in reduction of annual risk cost and compared with the cost of implementing these upgrades. Results are shown in Table II.

In Table I, there is an item for “loss of travelling screen motor”. This is a filter cleaning system that was identified in the reliability study as a weak link that is not backed up to the same extent as the power system components are. The failure rate of this travelling screen motor passed the 6-hour failure time criterion for a catastrophic system failure because of special motor mounting arrangements that makes the motor difficult to be replaced within the six hours.

The travelling screen motor failure was easily handled by stocking a spare motor with the particular mounting arrangement so that a failed motor can be replaced within the time before catastrophic failure occurs and this particular mode of failure was eliminated.

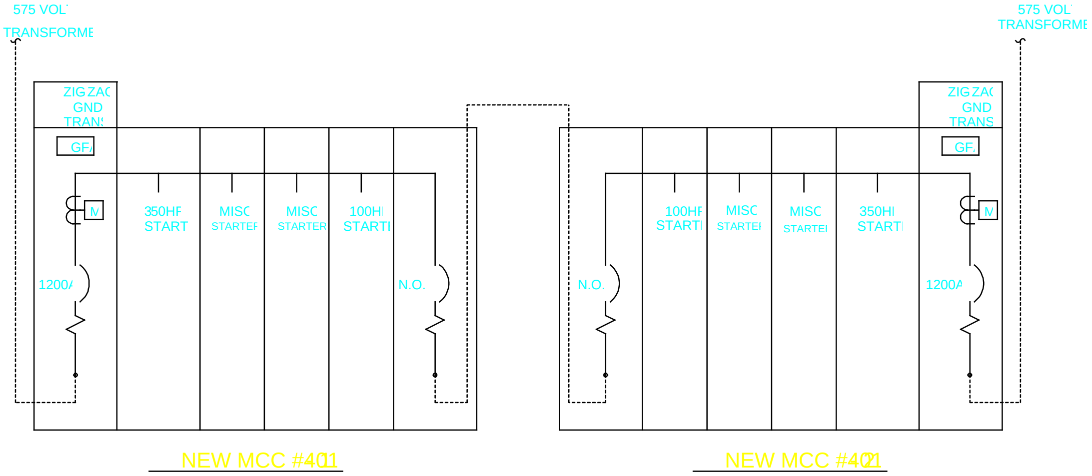

Fig. 2. Reliability Upgrade, Option No. 1 - Split 1200 A MCCs with Tie Breakers

TABLE I
PUMPHOUSE CUT-SETS OF EXISTING ELECTRICAL SYSTEM

Cut Set	**λ Failures per year**	**Critical Demand Period (months/year)**	**Adjusted λ Failures per year**	**Annual Probability of Failure F1**	**30-year Probability of Failure F30**
1. Loss of switchgear PDP#401-1	0.01428	6	0.00714	1:140	1:5.2
2. Loss of main and standby transformers	2.0 E-6	6	1.0 E-6	1:1.0 E+6	1:33,333
3. Loss of traveling screen motor	0.0824	1	0.00687	1:146	1:5.4
Pumphouse Totals			0.014	1:72	1:2.9

TABLE II
ANNUAL RISK COST SUMMARY FOR PUMPHOUSE SWITCHGEAR

Description	Annual Probability of Power System Failure	Cost of Recovering From a Prolonged Power Failure	Annual Risk Cost ARC
Existing switchgear installation	1:140	$100 million	$714,286
After Switchgear Upgrade Option #1	1:1.25 E+6	$100 million	$80
After Switchgear Upgrade Option #2	1:1470	$100 million	$68,027

POWER SYSTEM FOR PRODUCER GAS MANUFACTURING PLANT

Plant Background and Need for Study

The second example of a power system reliability study is a producer gas plant in southeast Asia. The plant is relatively new and well designed with full capacity standby generators and redundant feeders and transformers within the plant so that plant production is not seriously affected by any single electrical component failure within the plant.

The gas production process consists of eight independent trains so that failures of any process equipment usually only affect one of the eight production units and do not significantly affect the overall plant output.

However, while the plant reliability within the plant boundaries is excellent, it is deeply affected by factors outside the plant boundaries that are beyond their control. Outages can be catastrophic because the plant is the only significant gas production facility in the area supplying consumers in a large metropolitan area. It is not part of a gas utility grid supplied by several production plants. There is gas storage within the piping system to sustain consumer demand for a period of time but a prolonged outage leads to unacceptable drops in pressures within the piping system.

The generators in the plant are fully rated to run the plant but they are on a standby basis. The gas production process is a continuous process with exothermic reactions that is disrupted by the generators' startup and transfer times. Restarting the process depends on process conditions and may take a long time if the process has cooled off.

Plant management took preventive measures to commission a power system reliability study to quantify the risks of the gas plant production failure due to electrical power system failure and to identify remedial measures that will reduce their risk exposure.

Reliability Model

A reliability fault tree model was created to show the effects of various equipment failures on the overall plant failure rate. Plant management defined plant failure as the failure of enough production units to reduce plant production levels below maximum gas consumer demand. This definition effectively identifies the redundant production capacity of the plant.

Electrical system failure was defined as system voltage dropping below the motor bus undervoltage protection setting. This definition follows from the plant experience of surviving through short term dips but was not able to recover once the motor control circuits were interrupted.

Since all the plant electrical systems already have redundant feeders and power transformers and because their failure does not affect more than one or two production units, it became clear from the model that the electrical utility reliability was a major cause for concern. Simultaneous failure of the two electric utility feeds affects the complete plant in that all the production units are interrupted during the transfer to standby generators.

Once production is interrupted, xtensive plant personnel are required to bring as many production units back on line as possible to meet gas demand and it is not practical to staff and train enough people to be on standby tohandle this start condition.

Discussion with the electric utility was informative but not definitive. The electric utility insisted that they have the most reliable supply possible with a redundant transformer in their substation backing up two transformers that feed the dual utility feed to the plant. Efforts in defining the failure rate of the utility supply were unsuccessful as the electric utility did not want to imply any guarantee on the reliability of their supply.

While the immediate utility connections to the plant are relatively secure, the utility is prone to system wide failures due to lightning and equipment failures, which can lead to simultaneous failures of both feeders to the plant.

We eventually settled on the industry average failure rate for dual utility supply as listed in the IEEE standard. We checked this figure against plant experience with their utility supply and found it to be within the experience range at the plant site.

Overall, the reliability model identified the electrical utility failure rate as the most significant cause of plant failure and the other causes of plant failure were one or two orders of magnitude lower in probability. This is not a reflection of poor reliability of the utility supply but rather the high reliability standards required in the plant and the fact that the plant components are already several orders above average plants in reliability.

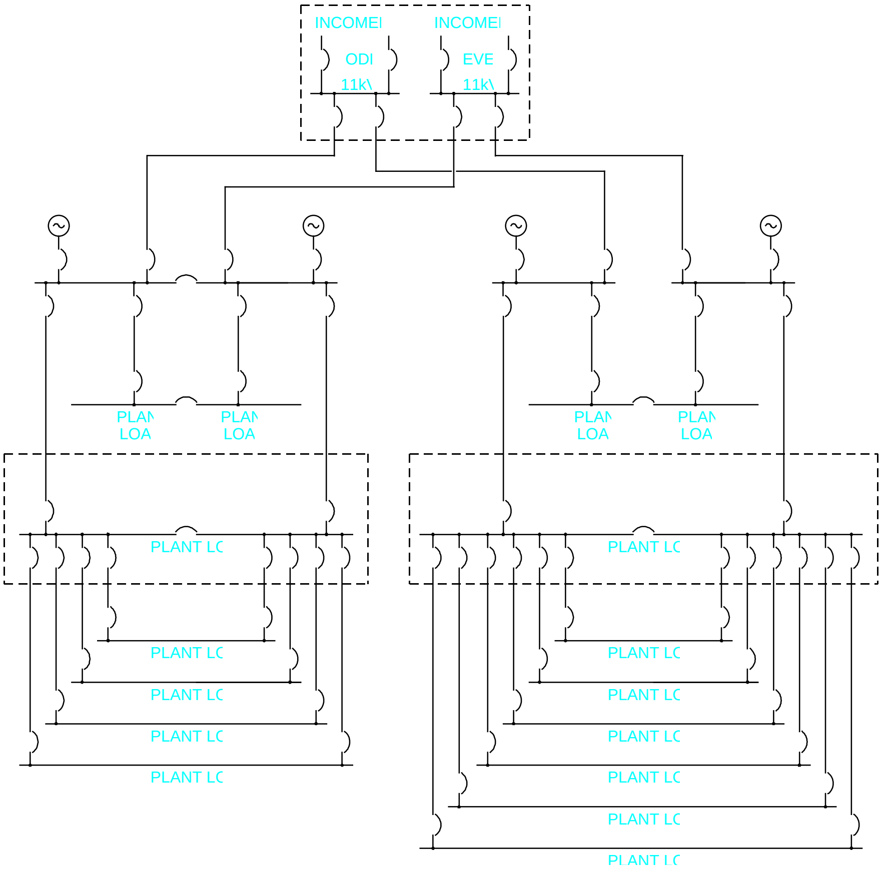

Fig. 3. Simplified One-Line Diagram for Gas Plant

The reliability model also uncovered some maintenance considerations where the plant reliability may be compromised when parts of the system are de-energised for maintenance leaving no redundancy to back up production. While the effect on reliability is limited due to the relatively short intervals when the system is being maintained, the reliability model was useful in showing alternate system switching arrangements so that production reliability is not compromised during maintenance.

Options Considered to Improve Reliability

Options to improved the plant electrical system reliability were:

- Support the complete plant load by UPS;
- Have generators running continuously or synchronized with the utility so that the plant load can be supported immediately upon electric utility supply failure;
- Modify the process to allow easier restart after a power failure and to implement automatic sequence start to reestablish the process.

Recommended Actions

The final recommendation accepted by the plant included three main actions:

1. Automate the utility-to-generator transfer so that generator power will be available within a definite time without uncertainty associated with human error possible in manual transfers. The electric utility recently approved the concept of automatic instead of manual transfer to the standby generator system.
2. Provide UPS for critical process motors so that the process can be kept in a holding pattern with minimum product flow for the duration of transferring from utility to generator power. Restarting the process from this hold position is much easier since process temperature and pressures are maintained within operating limits and no purging will be required.
3. Implement automatic sequential starts to restore process motors and valve configurations to conditions prior to power failure. This system cuts down the demand on process startup personnel and also prevents human errors during startup.

CONCLUSIONS

Quantify Reliability

The common theme for both examples is the value of quantifying electrical power system reliability.

In the aluminum smelter example, quantifying system reliability provided the justification for the system upgrade to reduce the risk of a very expensive smelter shutdown. It also provided the reliability target so that money is not spent on the electrical system out of proportion to the reliability of the mechanical and civil considerations of the site.

In the producer gas manufacturing plant example, quantifying the electrical utility reliability identified it as the main cause of concern. Without failure rates, discussion of system reliability becomes a relative term and it would be impossible to consider an electric utility's claim of having a very reliable supply when referenced to a plant's internal power system reliability.

In both examples, quantifying reliability allow the plants to prioritize their actions and gauge the importance and urgency of the actions required based on the probability of failure provided by the reliability model. The actions taken cost much less than the potential damage that can happen and the cost of the reliability studies themselves was insignificant compared with overall project costs.

Following the classic approach to solving large complex problems, the reliability model also allowed the system to be properly isolated in smaller subsystems. Each subsystem can be considered individually and then later on coordinated into an overall picture for the complete plant.

REFERENCES

IEEE Standard 493-1990, "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems"