Abstract - This paper is written to help users to make the right decisions about what devices in a Plant supply need to be duplicated and how to decide when it is no longer appropriate.

In the first part of this paper the mathematic theory behind the mechanism of failure is explained. This is followed by a chapter that explains the different strategies that can be followed to cope with failures. Redundancy as one of these strategies and will be explained in more detail in a separate chapter. The second part of the paper explains how these strategies are implemented in practice looking more closely at power supply. The paper finishes with an with thumb roles for configuring a power supply.

I. INTRODUCTION

Looking at electrical supply systems as a whole and the part played by process controls in these systems, it is apparent that more and more process controls are being connected to devices within electrical power systems to obtain information on the status of these systems. In many cases the process controls form part of the electrical power system, for example intelligent motor control or intelligent feeder protection systems that use serial communication to give detailed information about the electrical power system. This information is than used to adjust the process.

Petroleum and Chemical Industry systems need to be safe. Safety is partially dependent on the reliability and availability of the process equipment. Redundancy is often used to achieve this reliability and availability. Redundancy is commonly achieved by a proven configuration of duplicate components. For example, for each function there is 'A' and 'B' equipment (e.g. pump PM-9011-A and PM-9011-B). In normal operation one of the two is operating and the other is on standby (and available for maintenance). If the operating equipment fails, it is easy to switch to the standby equipment.

This involves increased capital and operating costs but will ensure higher system availability. However, one question that must be asked is: Is there potential for a common failure? Can a failure occur that will affect both A and B. In this case all the cost and effort of duplicate equipment would be worthless.

II. THEORY OF FAILURE

Every device within a system has the potential to fail. To be able to cope with these failures it is necessary to quantify the possibility of failure.

A. Device Failure

Analysis of the failure rate of each device will give an indication of the likelihood of failure occurring. Extensive analyses and lifetime experience of devices have produced records of failure rate for many devices. These failure rates are often expressed as the rate of failure of a device that can be expected in one billion \((10^{9})\) hours of operation. This can be translated to a more practical expression of failure frequency or, expressed in positive terms, the probability that a device will be available and able to perform its intended function. This can be expressed by the formula:

\[
A = \frac{1}{F_f} - r_t
\]

Where:
- \(A\) = availability of the device
- \(F_f\) = mean failure frequency of the device
- \(r_t\) = mean repair time of the device

B. MTBF

Within an engineered system the frequency of failure is commonly expressed as a failure rate, or Mean Time Between Failures (MTBF). In the special case where the likelihood of failure remains constant with respect to time (i.e. it is not dependent on use or environment), and ignoring the time to recover from failure, failure rate is simply the inverse of the MTBF. MTBF is an observed figure, typically presented in manufacturer's data, and therefore subject to very large deviations.

C. System Failure rate

Petroleum and Chemical Industry systems comprise a combination of devices. Each device has its own failure frequency. The probability that a total system will function correctly is dependent on the probability of each device performing correctly, as shown in the formula below.

\[
F_{f, total} = F_{f, device 1} + F_{f, device 2} + \ldots + F_{f, device n}
\]

Where:
- \(n\) = the total number of devices in a system
- \(F_{f, total}\) = mean failure frequency of the system
- \(F_{f, device}\) = mean failure frequency of the separate devices

This means that the failure frequency of the system is largely determined by the failure frequency of the weakest device in the system. If more devices are added (in line) to the system, the failure frequency will increase.

Reducing the system failure rate will directly increase the system availability.
D. Duplicate devices

A way of increasing the system availability is by duplicating devices. Each duplicate device added to the system decreases the probability of system failure according to the formula:

\[
F_{t\text{ total}} = \frac{(F_{t \text{ device 1}} x F_{t \text{ device 2}})}{(F_{t \text{ device 1}} + F_{t \text{ device 2}})}
\]

Where:

- \(F_{t \text{ total}}\) = mean failure frequency of the system
- \(F_{t \text{ device 1}}\) = mean failure frequency of the separate devices

This means that if a single device has a failure frequency of three times a year, dual devices will have a failure frequency of only 1.5 times a year. This formula assumes independence of failure events (any single device is sufficient to keep the system running), and no common mode failures.

E. Common mode of failure

A common mode failure occurs when events are not statistically independent, i.e. one event causes both devices to fail.

F. Ambient influence

Tables of device availability and/or failure rate are available but the figures do not normally indicate the influence of the environment on the failure rate. In all cases where environmental influence is not mentioned it is clear that optimal conditions are assumed. If a device is operated in an ambient condition that is more severe than the design ambient condition for the device, this will cause an increased failure rate on the device and adversely affect the system availability. In general the device must be operated within design limits, ambient conditions and rated (electrical) operating parameters.

G. Maintenance influence

In this paper, only the design aspects of failure in a system are reviewed. Maintenance and controlled conditions have an impact on reliability of a system. For instance, the time to repair can be reduced by condition-based monitoring, but whatever maintenance is carried out, this will not help if the equipment has an excessively high failure rate to begin with.

III. STRATEGY

After determining the failure frequency of the system it is necessary to indentify if this is acceptable in terms of the requirements. Most commonly the failure frequency is compared to the availability required of the system. To determine if measures should be taken to increase the availability (decrease the failure frequency), a simple cost and benefit analysis will quickly give an answer, yes or no.

In these cases an FMECA (failure mode, effect & cause analysis) is made to look at the whole system instead of just one area. To get an indication of the appropriate investment, the financial cost of non-availability of the system needs to be calculated.

Once the need for a reduction of the failure frequency has been determined, a strategy to decrease the failure frequency needs to be chosen.

A. Preventing failure

One of the strategies that can be used to improve the availability of a system is to prevent failures. Some devices will have a function that can be achieved by using a completely different solution. The question needs to be asked, can we change this function to an inherently safe function.

For example, the pressure in a fluid system can be achieved by a controlled pump, but the same effect can be achieved by using a header tank to give the required head of pressure. This is an inherently safe option, as long as gravity works! However these systems are often expensive and impractical.

B. Reducing the chances of failure

One way of increasing availability is to reduce the chances of failure of the separate devices. This involves making a critical selection during engineering of a system;

1. Selecting devices with a lower failure frequency.
2. Over-sizing devices.
3. Selecting the right ambient condition.

Some devices will be available on the market with a choice of characteristics. These characteristics may have different failure frequencies. Selecting and using the device with the lowest failure frequency will help increase the system availability.

Some devices will perform with a lower failure frequency if less is asked of them. Working below the nominal load will increase their lifespan and lower the failure frequency. Sizing a device so that it operates below its rating will normally help increase the system availability. Working below the maximum ambient conditions (or above minimum ambient conditions) will increase there lifespan and lower the failure frequency.

Most devices will have a higher failure frequency if they are used in an ambient condition which is above the device specifications. For example a simple air conditioner designed for a maximum ambient temperature of 35 degrees Celsius will work perfectly until you need it for real at a higher temperature.
C. Decreasing the probability of failure

The probability of failure of a function can also be reduced, without changing the failure frequency, by duplicating the devices that perform this function. This strategy is widely applied. The benefits and traps of this strategy are described more detailed in chapter IV, Redundancy.

D. Containing Failure

A different strategy is to limit the effect of a failure, by adding a device that acts as a safety net. This device will not affect the failure frequency but will reduce the effect of a failure. For example, nearly all tanks containing hazardous chemicals are required to have containment barriers around them to contain 100% of the volume of the tank in the event of a catastrophic tank failure. Similarly, long pipelines have remote-closing valves installed at intervals along the line so that, in the event of failure, the entire pipeline is not lost. The purpose of all such containment systems is to limit the damage done by a single failure.

E. Reducing the time to repair

Without changing the failure frequency of the system the availability can also be increased by shortening the time to repair, also known as MTTR (mean time to repair). This involves making all devices easy to repair or replace. This strategy is also known as minimum down time.

F. Standardization

A site philosophy based on standardization will improve the total system availability by lowering the failure frequency and lowering the time to repair. It will lower the failure frequency because ultimately the equipment with which one has the best experience (reliable) will become the standard. It will lower the time to repair because of the knowledge the user will have accumulated about the devices used. Both maintenance engineers and design engineers will have more knowledge and experience with the particular device and therefore more prompt action can be taken when a failure occurs. This will result in shorter downtimes. Time to repair is reduced even further because standardization of devices will increase the availability of spares from stock. An additional advantage of standardization is a reduction in detailed engineering costs. Although initial costs might be high, total cost of ownership will be relatively low if standardization is applied with discretion. One disadvantage of standardization is that it can be overdone, compromising flexibility and influencing the effect of a failure. One should aim for a practical balance, often based on local site experience.

G. Combination

Practical solutions are mostly found in a combination of these strategies.

IV. REDUNDANCY

A strategy to reduce the probability of failure of a function is by duplicating the devices that perform this function. This strategy is widely applied. The definition of redundancy is:

Duplication of components or circuits to ensure survival of the total system in case of failure of a single component.

In electrical power systems, the term redundancy indicates the use of duplicate devices. However, in process control systems, redundancy is defined as a system that consists of several different devices with the same function and a decision system that verifies the outcome. Different definitions may be used within process control systems and electrical power system. Since process control and electrical systems are connected this can cause confusion. Process control systems are connected to the electrical supply to enable them to function but there is an increasing trend for process controls to be connected to devices within the electrical power system, to obtain information on the status of the electrical power system. In many cases the process controls are an integral part of the electrical power system; for example, intelligent motor control or intelligent feeder protection that uses serial communication to give detailed information obtained from the electrical power system. This information is than used to adjust the process.

All this means that there are different perceptions and redundancy is confused with configurations were a single device function is replaced by a function in which duplicate devices can perform this function. In this paper the type of configuration that is used to lower the failure frequency will be called duplicate devices.

A. Duplicate devices

The principle of duplicate devices assumes that, when events involving failure of devices are statistically independent, the probability of a joint occurrence is low. For example, if the probability of failure of a device is one in one thousand per year, the probability of the simultaneous failure of two devices is one in one million per year, (provided that the two events are statistically independent). This principle favors the strategy of using duplicate devices or parts (See chapter Nomenclature for the glossary of terms used).

One practical benefit of duplicated devices is that it is possible to take advantage of duplication to cover device outage for maintenance. One device can temporarily be removed from the system for maintenance without the need to stop the system.

B. Common mode failure

To achieve maximum benefit, duplicate devices should be statistically independent; there should be no common mode of failure. But not all common mode failures are easy to detect because they are not always directly linked to the function of the device. As indicated in the examples below common failures can be unexpected:

1) An example of this is when devices are all located in one room. If the room becomes too hot, the devices may all fail at essentially the same time, from a common cause (the heat in the room). This can be
eliminated by using separate locations. However, it is not always possible to eliminate all common mode failure, for example, in the unlikely event of a Richter 10 earthquake.

2) For example, if a single electrical power supply feeds duplicate devices, failure of that supply would be a common mode failure.

3) The power supply for the process controls can produce a common mode failure. If the power to the process control is lost the process will come to a standstill. Hence uninterruptible power supplies are used to feed the process controllers.

4) For example, process controls was fed by redundant UPS systems having batteries with a runtime of 2 hours. But failure of the ventilating and air conditioning brought this down to 10 minutes. The common mode of failure (power failure) was identified and tackled. But even the solution needs to be free of common failures. In this case cooling redundancy was as critical as electrical redundancy.

5) Another source of common mode failure within the process control system is the communication line between the power system devices and the control system. If efforts are made to improve the availability of the power system, than similar efforts should be made to duplicate these communication lines.

To achieve the full benefit of duplicated devices, all risks of common mode failure should be identified and eliminated.

V. POWER SUPPLY

![Figure 2: General power supply configuration.](image)

The power supply system can also fail. All the strategies described above can be applied to the power supply system as a whole. The cost of power reliability problems to the end users are higher end growing as the dependants on electrical power is increasing. According to the Distributed Energy Resources Program and Strategic Plan [2], the cost of downtime by industry was estimated as indicated in table I.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Avg. Cost per Hour* [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular Communications</td>
<td>$41,000</td>
</tr>
<tr>
<td>Telephone Ticket Sales</td>
<td>$72,000</td>
</tr>
<tr>
<td>Airline Reservations</td>
<td>$90,000</td>
</tr>
<tr>
<td>Credit Card Operations</td>
<td>$2,580,000</td>
</tr>
<tr>
<td>Brokerage Operations</td>
<td>$6,480,000</td>
</tr>
</tbody>
</table>

*Note: Costs inclusive intangible loss, including lost customers, damaged reputation, etc.

Generally the power supply can be divided in three major parts; generation, distribution and consumption. Failure of the generation system most often causes a common mode failure for the process. Failure of the distribution system normally has a smaller impact, affecting only part of the network. Consumption consists mainly of consumption of the devices themselves (e.g. motors and heaters). To strategy to reduce the probability as described before can be applied on the power supply system as well.

A. Preventing failure

Prevention of failure is always the best solution but this can be very costly. Prevention of failure in the electrical system is usually done by protecting the electrical devices by an enclosure. In the past, open switching devices were common. Modern switching devices are more often sealed or closed, thereby providing protection against open arcing. Modern switching devices are also very small and have fewer parts. This means that they are less susceptible to failure.

B. Containment the failure

Without changing the failure frequency of the system the availability of the system is also increased by containing the failure. In an electrical system this can be achieved by segregation of the devices. The segregations should not only be a visual segregation but designed to contain the failure. In an electrical system this can be achieved by segregation of the devices (MCC’s) with adequate segregation of the different devices/functions. So the failure of one functional unit (e.g. bus bare, feeder, motor starter, or cable connection) is contained to only that unit; other units will not be affected.

C. Reducing system failure rate by “over sizing”

Many of the failure mechanisms in electrical systems distribution are influenced by the temperature limitation of the isolating materials. This temperature is an combined result of ambient temperature and load(losses). There for the load is has an affect on the failure rate. For instance if a cable is operated above its nominal rating, it will heat up and will degrade faster. Even short time overloading of the system will increase the failure frequency. Therefore the electrical system needs to be sized to accommodate for the worst-case load.

D. Common mode of failure

The supply or generation of electricity could be a single device. This would mean that if it fails all the distribution equipment and all of consumption devices will fail. Therefore the supply is always a common mode of failure. But common mode failure can also exist in the distribution network, main transmission cables or main transformers. The most practical solution to this problem is to have a double source of supply, as shown below.
If one power supply fails, the most effective way of switching these two power supplies will be to re-route the electrical power from the good supply, in such a way as to create a new double system from the point of failure onwards. However, the connections between the two systems should be designed to operate as two independent systems. This idea of double supply has a maximum effect if it is implemented right through the network to the lowest possible level.

E. Hidden Common mode failure

If a redundant power supply system is needed all common mode should be eliminated, but they are not always easy to detect, as indicated in the examples below common failures can be unexpected:

1) Switchgear is the main component of the distribution system. The switchgear consists of several switching units, each protected by a sophisticated protection system. The protection devices are generally microprocessor-based and need an auxiliary power supply. Furthermore, although the switchgear is carefully designed to fulfill all the requirements of duplicated systems, it is not uncommon for the auxiliary supply to be derived from a common source and looped from device to device. Failure of this source will cause failure of the whole switchgear system. Failure of the wiring between the devices will also cause failure of the total system.

In systems where extreme availability is required (e.g. ships or nuclear installations) not only are the control components doubled but wiring is also run in separate cableways to eliminate common mode failure due to fire etc.

2) A common problem in nearly all plants is failure of the uninterruptible power supply (UPS) feeding the auxiliaries. During a blackout the UPS is essential to get the system started again. But the UPS is an expensive device and maintenance-sensitive. Frequently the UPS is used for more than one function. Some loads (for example emergency lighting) will drain the UPS during blackout. The capacity of the power supply is limited, so when the problem that caused the blackout is resolved there may be no power left in the UPS to re-start the system.

3) A less well-known common mode failure occurs as a result of harmonic distortion or transients in the power supply – everything is well configured, all possible failure of separate devices is covered, and than all the connected devices show abnormal behavior. The devices are switched off by their trip units. The failure rate may increase with no clear evidence of common failure. When such situations arise, the electrical power supply quality is most likely to blame. Harmonic distortion and/or transients are always caused by a combination of an imperfect power supply and an abnormal load. Grid calculations or grid simulation will help to indentify these situations.

4) Within process equipment the electrical power is not the only power source. If distributed gas, pressurized air or steam is used, these power sources can cause common mode of failure as well. There for these power sources should be configured like an electrical grid with dual reducers and intelligent “switching” possibilities, to reduce the changes of a common mode of failure.

5) Finally, there is the human factor in common mode failure. An inexperienced maintenance engineer may perform incorrect maintenance on the devices and so cause the frequency of failure to increase. Even worse, incorrect maintenance procedures may mean that all maintenance engineers carry out the wrong maintenance. For example, wrong calibration of a measuring device will cause a faulty reading without anyone knowing.

F. Ambient condition

Placing an electrical device within the environment for which it is designed for will benefit the failure rate. If a device is placed in an environment which is too harsh, it will have a much higher failure rate. Matching the specification of the device to the environment is critical. For instance, an excessively dusty environment will damage the installation but too high a degree of protection (IP rating) may cause the temperature to be too high.

Vibration is another ambient condition which will influence electrical systems. Decouple the electrical equipment from the vibrating source should bring the failure rate back to normal values.

G. Reducing the time to repair

Availability can be increased, without changing the failure frequency of the system, by reducing the time to repair. This can be achieved by using devices that are easy to repair or simple to replace. A device that is easy to replace may be removed for repair without affecting the system’s availability.

H. Redundancy

The probability of failure can also be reduced, without changing the failure frequency of devices, by using duplicate devices to perform one function. Transformers are often doubled in a power supply system. Main switchboards are divided into several sections with the switchgear divided into separate, parallel systems.

A common method used to improve the reliability of a power supply system is through duplicating the devices, for example more than one transformer in a substation. Typically, each device has sufficient capacity, perhaps based on an emergency rating, to carry the peak load that...
the system may be asked to deliver. Such full duplicated devices are effective in improving system performance but are usually quite expensive. If the load on the system is variable, there may be an opportunity to cut costs by reducing the capacity of duplicated devices to a level less than that required to carry system peak load without overloading them. An overload might result in an actual disconnection of the load or, perhaps, a reduction in the life of the overloaded component, depending on the protection scheme in service.

I. Standardization

For withdrawable motor control centers it is beneficial to use the same devices in all drawers, as far as is practicable. If a failure occurs, the relevant drawer is easy replaced with a drawer having the same function. Standardization of a low voltage intelligent MCC, means that both the motor starters and the intelligent modules need to be designed to fulfill similar functions. For example, in a withdrawable MCC some motors may have a remote ammeter and others may not. For maximum interchangeability it is good to equip all motor starters with the same equipment even though it may not be needed in all applications. This has the advantage that, if you need to swap units, the drawers are all the same and there is no motor-specific adjustment required. The same is, of course, true for intelligent modules; they should be of the same type and fully equipped so that no motor-specific adjustment is required (reconfiguring, buying new licenses etc.)

If the same equipment is used on all locations, maintenance engineers and design engineers will have better knowledge and more experience with the particular device and therefore prompt action can be taken to rectify problems. This results in shorter downtimes. Standardization of devices means that even the use of build-in spares is possible. This will further reduce the time to repair.

J. Combination

In electrical systems it is easy to combine redundancy requirements and repair requirements by installing duplicate devices which can be isolated from the system. In normal operation two devices are available, thereby increasing total system availability. In case of failure of one device, it is easy to replace the failed device without disturbing the system.

VI. HOW TO CONFIGURATE A POWER PLANT SUPPLY

Within process equipment and process controls, the power source is usually common and can cause common mode failure. A simple but effective way to get a well-designed power supply is described below. However, before starting to design the power supply, a thorough understanding of the process operating conditions is necessary.

1. Determine what the critical parts of the process are and what needs to be in operation as a minimum to ensure production.
2. Consider whether it is still worthwhile having one part in operation if others are down. Can the process be divided into separate process parts?

3. Ask how critical is the process? Will a short downtime (seconds or minutes) create high production losses or do you have hours available for repair? Can you catch up with production (is there overcapacity installed and available?).
4. Financial justification should be based on total cost of ownership (TCO), including production losses in case of failure; an FMECA is often the way to make it transparent.

Figure 4 below shows a typical design in which redundancy can be added at all levels depending on the criticality of the individual devices/parts. In this design each HV switchboard has to be capable of supplying the full load of both systems. In case of failure or maintenance only 50% of production capacity is lost. In case of failure of one HV supply, 100% production capacity can be maintained. Utilities and process controls can be fed from either LV side.

![Diagram of power plant supply configuration](image-url)
VII. RECOMMENDATION

As shown in chapter II, the failure frequency of the system is dependent on the failure frequency of the weakest device. Therefore it is wise to match the failure frequencies of the devices in a system. It is a waste of money to use a device that will fail once every 1000 years if it is connected to a device that will fail every 4 months. Because:

The system is as strong as the weakest link.

A system consists of different devices. Adding devices to a system will increase the overall failure frequency. Conversely, removing devices and simplifying the system will improve the availability. So the lesson is:

Keep it simple

Devices are engineered to operate at nominal load. Operating above nominal load will age the device and raise the rate of failure.

Never operate above nominal load.

Tables of device availability and/or failure rate per device are available but these figures usually do not indicate the effect of environment on the failure rate. The device failure rate is adversely affected if it operates in an ambient condition that does not accord with the specification for the device, for example, the degree of protection (IP rating).

Match the device to the environment.

Using duplicate devices will halve the failure frequency. If a system decoupling configuration is added, maintenance is possible without disturbing the system. Dual devices and a well-configured power grid will make additional availability possible but using dual devices is only appropriate if the total cost of the devices is less than the cost of damage caused by the failure of single devices.

€ (Dual Devices) < € (Failure of the Function)

If a failure can occur that will affect both devices all these measures are worthless. Common mode failures will undermine all the cost and effort put into using dual devices. To enjoy the full benefit of duplicate devices, all sources of common mode failure should be identified and eliminated. It is necessary to look for sources of common mode failure outside the norm, such as HVAC systems in a data centre where failure of the HVAC system may bring the run time of batteries down from 2 hours to 10 minutes or less. In this case redundancy in the cooling system is more critical than electrical redundancy.

Think outside the box

A site philosophy based on standardization will raise the total system availability. It is advisable to use equipment with which one has the best experience, or make efforts to understand the characteristics of equipment with which users are not familiar. This will enable prompt action to be taken, leading to shorter downtimes. It will also increase the availability of spare parts from stock and offer the possibility of working with standard designs.

Follow a site philosophy based on standardization

VIII. NOMENCLATURE

Glossary of terms used; Efforts have been made to use consistent terminology in this paper. However it is possible that other branches of technology use terms that are different from those used here. Therefore the list below gives synonyms for the used terminology:

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Glossary of terms used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>Equipment or part</td>
</tr>
<tr>
<td>System</td>
<td>Devices working together to perform one function</td>
</tr>
<tr>
<td>Availability</td>
<td>The time for which a device is fulfilling its function</td>
</tr>
<tr>
<td>Failure frequency</td>
<td>Frequency of failures (failures/yr)</td>
</tr>
<tr>
<td>Failure rate</td>
<td>The rate of the failures (e.g. one failure every 6 months).</td>
</tr>
<tr>
<td>Dual devices</td>
<td>Dual equipment = Duplicate devices/equipment</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible power supply</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, ventilating and air-conditioning systems controlling the temperature in a room</td>
</tr>
<tr>
<td>TCO</td>
<td>Total cost of ownership</td>
</tr>
<tr>
<td>MCC</td>
<td>Motor control centre, in which each motor compartment fulfills all control and protection functions for the connected motor</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Duplication of components or circuits to ensure continued operation of the total system in case of failure of single components</td>
</tr>
<tr>
<td>FMECA</td>
<td>Failure mode effect &amp; cause analysis</td>
</tr>
</tbody>
</table>
IX. REFERENCES

[2] 2001 U.S. DOE Distributed Energy Resources Program and Strategic Plan,

X. VITA

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