APPLICATION NOTE
VOLTAGE DIPS: CASE STUDY

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SUMMARY

This Application Note describes an industrial case study in a nylon extrusion plant. Investigation revealed a history of disruptive dips at the plant with significant loss of production. Examination of the records showed that the plant was affected by faults in a wide area of the network. The objective of the study was to decide how to limit the exposure of the plant to these faults. The options for improvement include measures at the equipment, installation and network level. Several solutions are proposed and the cost of each estimated.

INTRODUCTION

This paper describes a voltage sag case study in Belgium. One of the industrial processes well known for being sensitive to sags is the extrusion of plastics in the textile industry. In this process, plastic chips are melted, transformed into filaments and finally wound onto drums. The fibres can be used to make, for example, carpets. Belgium is the largest exporter of carpets in the world and the second largest producer after the USA.

In order to obtain a clear understanding of the size of the voltage sag problem in Belgian extrusion companies, a survey was conducted among nine users of this process. In this study it was found that, on average, four production disruptions due to voltage sags could be expected each year. A thorough audit was carried out at one of these companies. The following three topics will be described:

- The production process
- The financial loss due to a forced production stop and the configuration of the electricity network
- Possible solutions that mitigate damage, considered from both technical and economic viewpoints

PROBLEM ANALYSIS

The company examined operates three processes that are vulnerable to voltage sags: Bulk Continuous Filament (BCF), Continuous Filament (CF) and Heat Set. In this document, we discuss the behaviour of the BCF process.

THE PRODUCTION PROCESS

Figure 1 shows the main sub-processes in a BCF extrusion line that produces textile fibre from polymer chips. The following steps can be distinguished:

1. The *extruder* melts the chips into a homogenous substance
2. The homogenous substance is pushed into a device that contains small holes (called a spin pump), resulting in a fibre (*melt spinning*)
3. Finally, the fibre is *stretched, twisted and wound* onto the spools

In each of these processes, several motor drives are used.

Simply from looking at the specifications of the drives and from discussion with the manufacturers, we already come to some interesting conclusions. The drives that are used in the chosen textile company originate from different manufacturers and consequently have their individual voltage sags immunity characteristics. In general, this immunity level does not significantly exceed the compatibility level of 90% (retained voltage) stated in the standard EN50160 [10].

If any one of the components trips due to a voltage sag, the entire process will be disrupted. This implies that the weakest link determines the response of the process to voltage sags and all components must be investigated separately. Manufacturers of textile extrusion machines also offer production lines with explicit immunity to sags. We did not investigate this option in detail, since this case study was conducted on an existing production line.

The first component, the extruder, is driven by a DC-motor. The motor is equipped with an analogue variable-speed control. In order to protect the power electronics in the drive, the under-voltage protection is set at a very sensitive level. It will shut down the entire process whenever it registers a voltage drop of 20% or more in one or more of the phases.

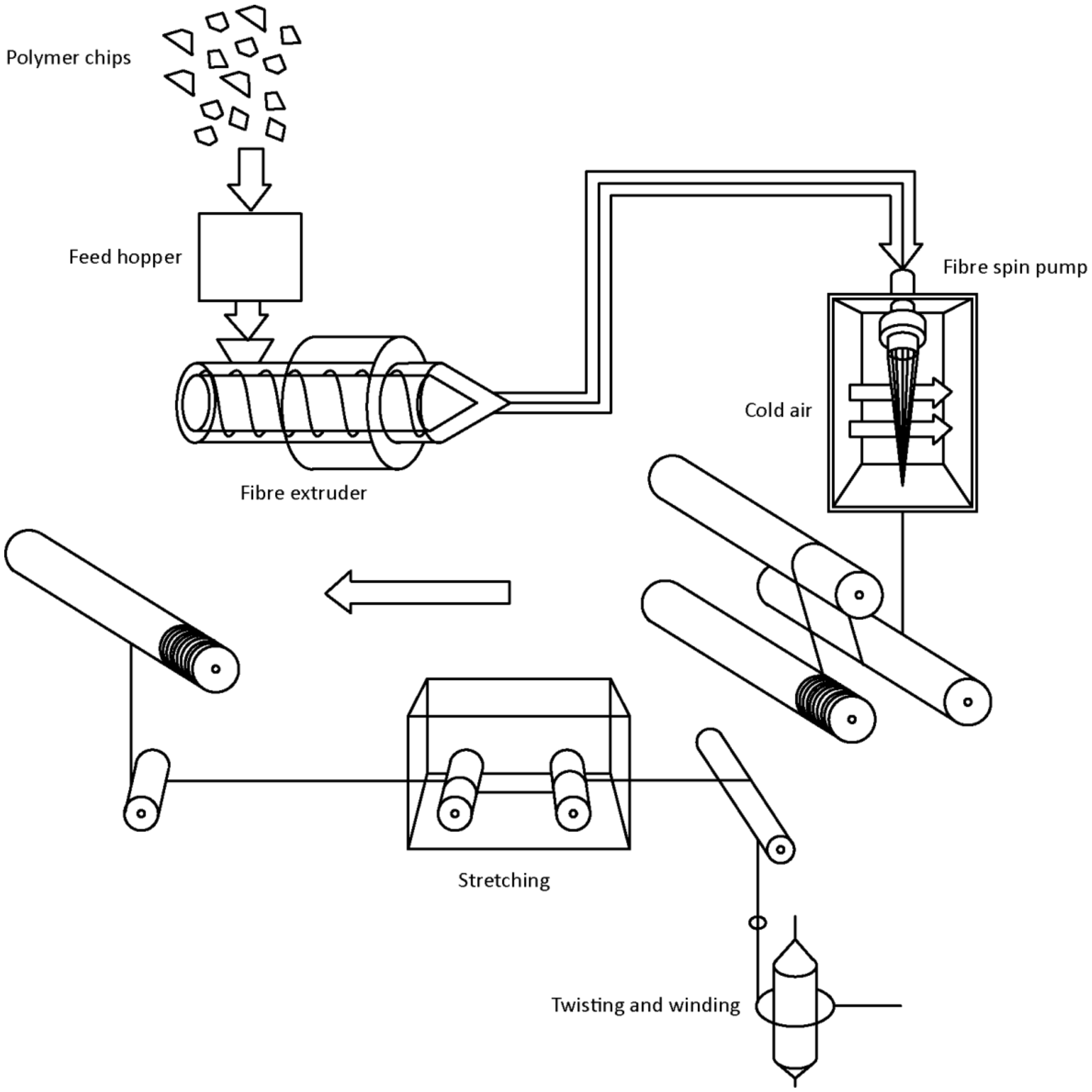

Figure 1 – The textile extruding processes.

The spin pumps are equipped with a variable-speed drive. The undervoltage protection of these drives will operate if the voltage of the DC-bus drops by 15%. Reference [4] shows that these appliances are always sensitive to three-phase sags and sometimes to one or two phase sags.

The stretching, twisting and winding is performed by variable-speed drives that are fed from a common DC-bus. These drives are equipped with kinetic buffering: the motors act as a generator during the sag and feed energy back to the DC-bus.

We conclude that both the drive of the extruder and the drive of the spin pump have to be taken into account when looking at mitigation methods.

Two further possible points of concern are process air and electronic process controls. Our investigation will show that it is not necessary to study these points in further detail.

FINANCIAL DAMAGE

Immediately after a sag which halts the process, the workforce begins to restart the process lines successively. Depending on the number of production lines (typically 10 to 20) the entire process may be normalized after two to four hours. This means that the average production outage ranges between one and two hours. There is no decrease in the use of raw materials during these four hours, because the extruder itself will be started immediately after the sag. If it were not, the remaining molten material would burn on re-heating and the burned particles would be extruded gradually over a period of several days, resulting in poor quality product. The cost of such a burn, therefore, would be much higher than that of discarding the excess polypropylene after extrusion. Furthermore, the workforce clean the devices themselves, so there is no increase or decrease in labour cost.

A major influencing factor concerning the financial loss is whether or not the factory production is continuous. In continuous production, as practiced by this company, the production lost during downtime cannot be recovered by working extra time, so loss of production translates directly into loss of profit – that is, the loss is equal to the value of the product not produced as a result of the downtime. In a non-continuous process, lost production can be recovered by overtime working, although there may well be additional labour costs.

ELECTRICITY NETWORK AND ORIGIN OF THE DAMAGES

Figure 2 shows the electrical network in the vicinity of the investigated extrusion company. The network is modeled up to the three connections to the 400 kV transport grid. The labels show the location and the dates (month/year) of the faults that have led to a process interruption during the monitoring period of 3.5 years. It can be seen that faults in the 15 kV distribution network cause most of the process halts. A sag meter installed at the electrical entrance of the extrusion company shows that most disturbances are three phase faults. Comparing the process interruptions with the output of the meter shows that the equipment is not vulnerable to three phase faults leading to dips with a retained voltage above 84%. Looking at the product specifications of the components, we conclude that the variable speed drives are certainly weak parts of the process. One of the possible explanations for the high occurrence of three-phase faults is the occurrence of excavation work for construction in the adjacent neighborhood.

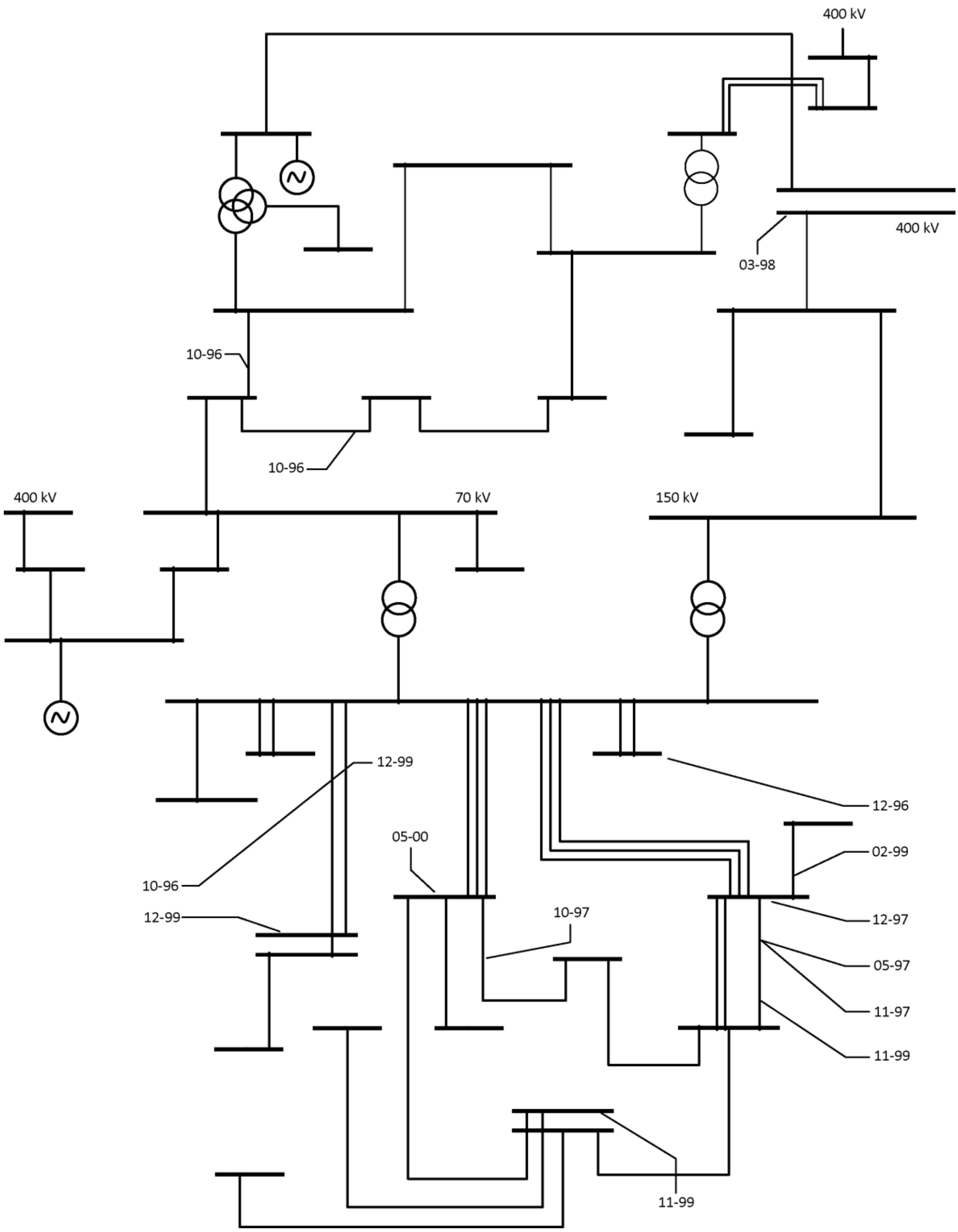

Figure 2 – Single line diagram of the electricity network indicating the dates of the faults (month and year).

AREA OF VULNERABILITY

The concept "area of vulnerability" (e.g. [5]) is used to visualize the retained voltage at the extrusion company due to a three-phase short circuit somewhere in the network. *Figure 3* shows this area of vulnerability for symmetrical three-phase short-circuits.

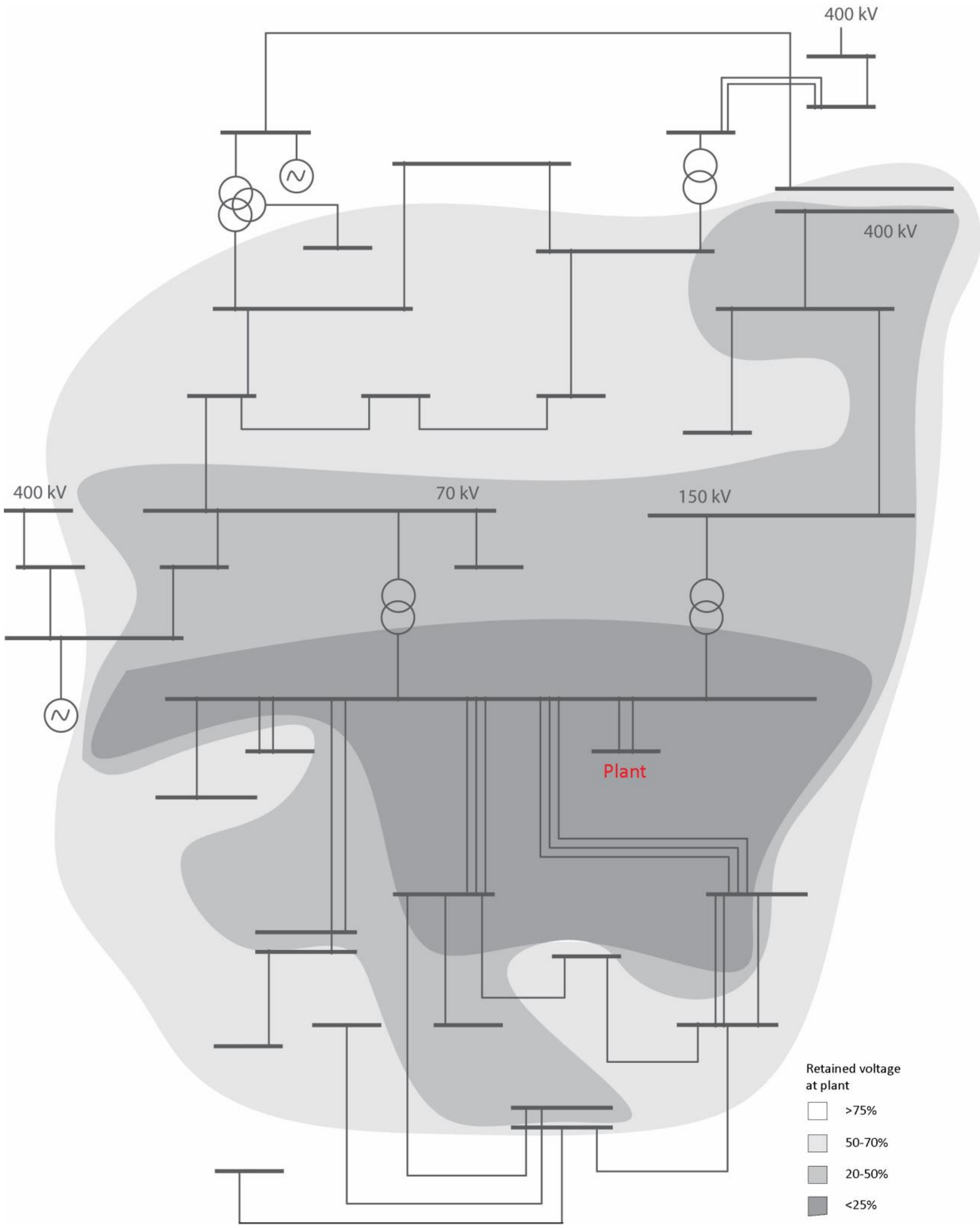

Figure 3 – Area of vulnerability.

Since it are these faults that cause most of the process interruptions, we do not have to use a sophisticated classification of voltage sags as described in [1]. Suppose, for example, that a cable or busbar in this network is situated in the grey area of 50-75%; this means that a three phase short-circuit at this cable or busbar will lead to a *voltage sag at the extrusion company* with a retained voltage between 50-75%.

Since the drives of the extruders and the drives of the spin pumps are vulnerable to any short circuits with a retained voltage smaller than 75%, we can conclude that a large part of the distribution network is situated in the area of vulnerability of the extrusion company. This has to be taken into account when investigating mitigation methods.

MITIGATION METHODS

Looking at mitigation methods we refer to a block diagram introduced in [5]. The four possibilities in this figure are investigated in the next sections.

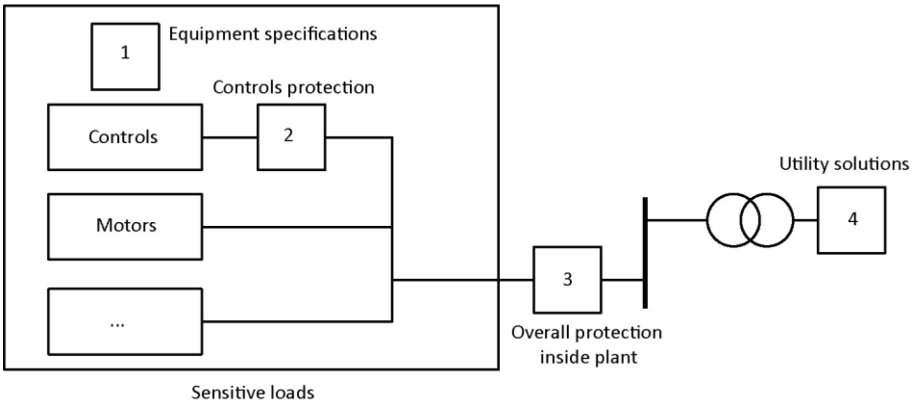

Figure 4 – Solutions to decrease cost due to voltage sags [5].

EQUIPMENT SPECIFICATION/CONTROLS PROTECTION

Before making changes to the equipment, it is important to make an inventory of all parts of the process that are vulnerable to sags. The fact that one piece of equipment trips first, does not indicate that all other items are immune to sags and there is a high risk that some other piece of equipment may trip once the most sensitive part has been protected. From the last paragraph we conclude that we certainly have to look at both the drives of the extruders and of the spin pumps. We must be aware that protecting only these drives does not guarantee a significant decrease in the number of interruptions due to sags since other parts of the installation can become the weakest link.

After discussion with the manufacturer of the spin pump drive, we learned that it is not possible to alter the drive because it is an analogue design and changing characteristics such as protection settings would require hardware changes. Due to the fact that the DC-bus of the Variable Speed Drives is not accessible from outside it is not possible to support this bus, for example with a boost converter [6] or an active front end [7]. Furthermore, from the manufacturer of the entire extrusion line we received the information that the drive cannot be exchanged for another due to software conflicts. It can therefore be concluded that further investigation in this area serves no purpose.

PROTECTION INSIDE THE PLANT

Several possible methods of protecting the system entirely or partially were investigated. The entire system has an apparent power of 1625 kVA. Because 955 kVA is only for heating purposes, we also investigated the protection of the process which drives the system. When only part of the system is protected, an additional static switch has to be installed, resulting in the topology of *Figure 5*. We first investigated the use of an Uninterruptible Power Supply (UPS) in the form of a flywheel with a diesel engine.

Secondly, we investigated other systems that only protect against voltage sags but not against outages. Examples of these systems are:

- *Dynamic Voltage Restorer (DVR)*: A DVR only adds the missing voltage to the voltage of the network (e.g. [8]).

- *DySC:* A DySC is a power electronic device containing a series sag corrector and a shunt converter that provides voltage sag immunity with a minimum retained voltage of 50% and 2 seconds, which covers 92% of the voltage sags that have been reported in a large study sponsored by EPRI [3]
- *Flywheel:* A flywheel without a diesel generator protects the equipment against all sags as long as the inertia of the flywheel can support the load. Most flywheels can supply the rated load for 3-15 s, which is sufficient to protect against all voltage sags but not against supply outages.

The purchase prices for all three the above mentioned sag mitigation devices do not vary substantially. However, one should take into account the costs of annual maintenance and stand-by losses. In that case, the DySC has the lowest cost. Taking into account that all recorded sags had a retained voltage exceeding 50%, we can conclude that all the above mentioned systems would have protected the process to these sags.

We also investigated the use of separate UPS devices for all the drives. This turned out to be far more expensive than the other options due to the large amount of power electronics.

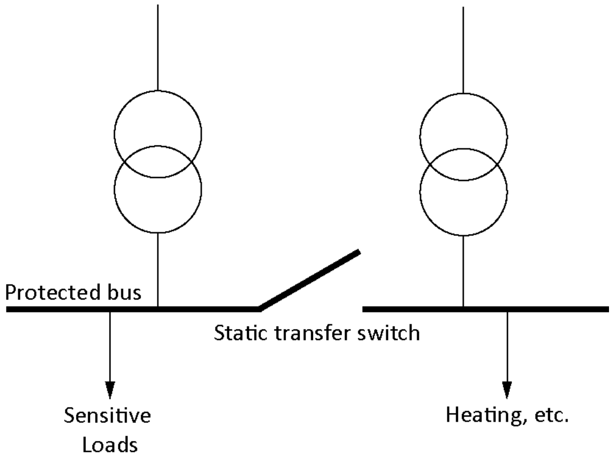

Figure 5 – Protecting a part of the process.

UTILITY SOLUTION: CHANGING THE ELECTRICAL NETWORK

Process outages can also be avoided by altering the network area. We examined two possibilities:

1) Adding a 10 MW generator
2) Restructuring the network configuration

The addition of a generator will uphold the remaining voltage according to:

$$\Delta U = \frac{S_g}{S_k} cos(\propto - \phi) \times 100 \qquad [9]$$

where

ΔU is the voltage increase in % of the rated line voltage

S_g is the rated generator power

S_k is the short circuit power

α is the phase angle of the short circuit impedance and

φ is phase angle of the generator current

A second option is to change the grid connection. In this option, the site would be connected to a different feeder, separated from the neighborhood.

Both possibilities are shown in figure 6.

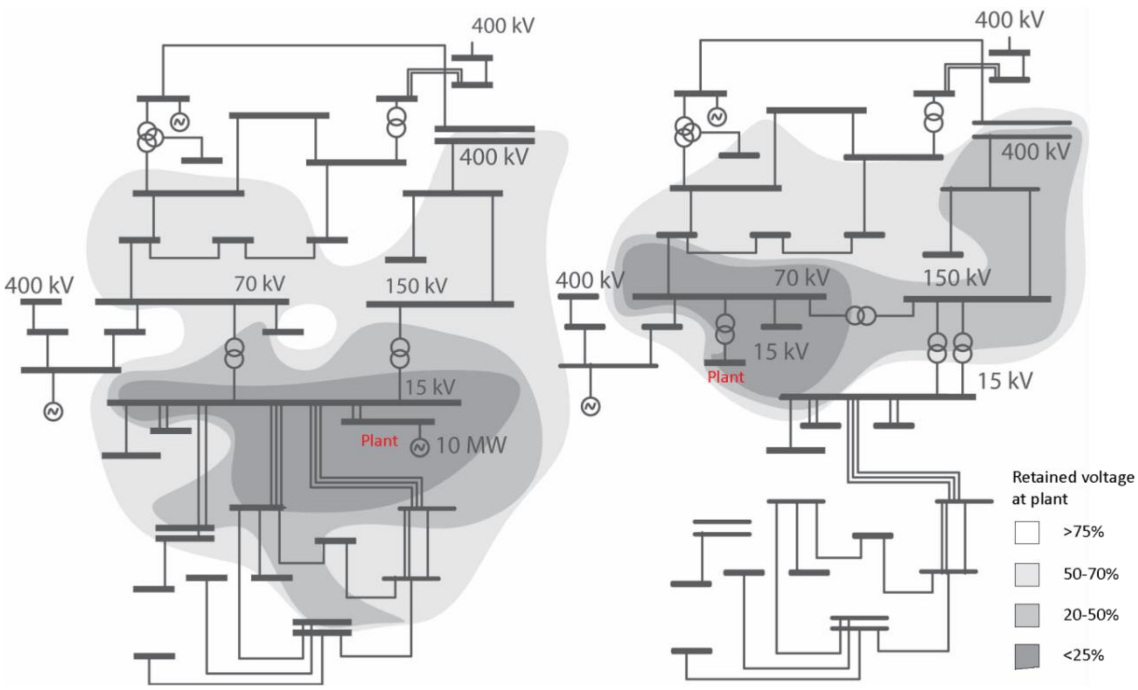

Figure 6 – Area of vulnerability by a) adding a 10 MW generator b) changing the network structure.

By comparing *Figure 3* with *Figure 6* (left), it can clearly be concluded that adding a generator of 10 MW will not help greatly. However, restructuring the grid (*Figure 6* (right)) will alter the area of vulnerability, significantly reducing the risk of damage due to voltage sags in the distribution system at 15 kV. An additional advantage is the fact that this restructuring will not only protect the BCF process but also the other two earlier mentioned processes (CF and Heat Set).

Since network adaptations were to be made by the network operator for other reasons, only the additional cost of separating the two busbars were billed to the extrusion company.

ECONOMIC ANALYSIS

When the different options are compared, two cost terms must be taken into account:

- The cost of losses attributable to voltage sags, bearing in mind that even after protective measures are taken, some reduced risk will still remain
- The cost of the protection measures

Whether or not a solution is seen as cost-effective also depends on the economic criterion that is used to evaluate the solution. For this study we use the Net Present Value method with a Required Rate of Return of 15% and an equipment lifetime of 10 years.

When we calculate the total cost of the described options we obtain the results listed in *Table 1* in which the cost of losses before mitigation is normalized to 100.

	Solution	Interruption cost (%)	Mitigation cost	Total cost
now	Current situation	100	0	100
A	Restructuring	26	62	88
B	UPS on complete BCF (1625 kVA)	60	303	363
C	UPS on parts of BCF (670 kVA)	60	152	212
D	DySC on complete BCF (1625 kVA)	60	109	169
E	DySC on parts of BCF (670kVA)	60	87	147

Table 1 – Comparison of the different mitigation options (cost before mitigation is 100%).

In case of a UPS, a maintenance and standby cost of 5% of the purchase price was assumed. For a DySC, this cost was assumed to be 1% of the purchase price. These costs were added to the mitigation cost.

The remaining PQ-costs of variant 'A' can be explained by the three faults in the transmission network (*Figure 2*). The remaining PQ-costs of the variants 'B' to 'E' are the costs of the un-protected CF and heat set process. *Figure 7* shows that only the option in which the network is restructured is economically attractive with the economic criterion specified.

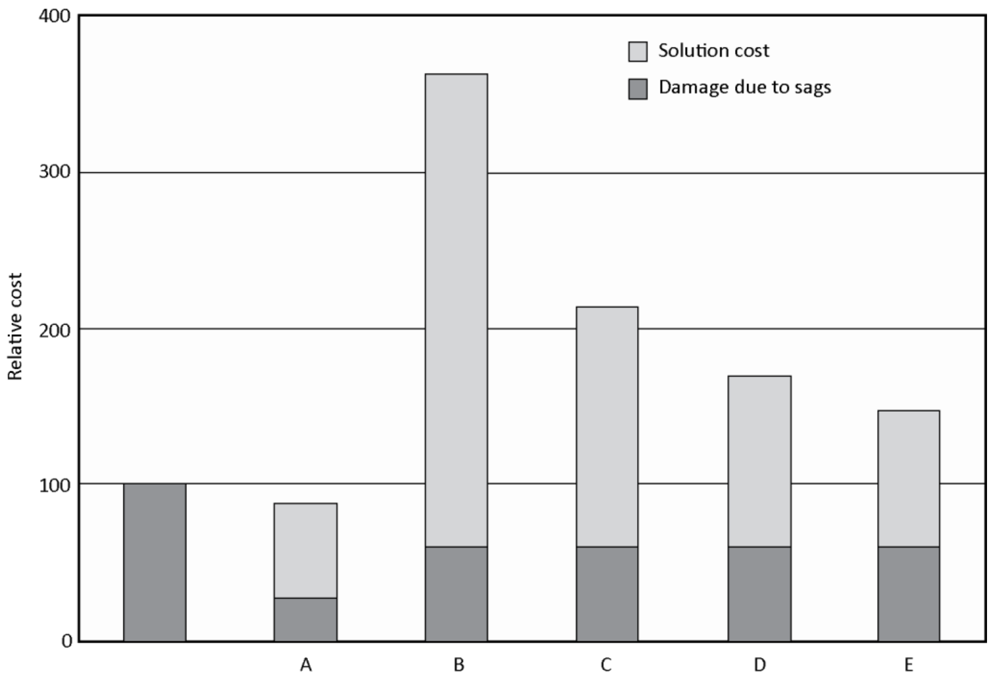

Figure 7 – Total costs for different options for a Belgian textile extrusion process as a percentage of base cost.

Although some companies consider a project horizon of 10 years for such an investment as being very long, this company decided to make the investment. They argued that some indirect or hidden costs, which are very hard to estimate, are not taken into account in this calculation. Such costs include, for example, discontent of the workforce due to breakdowns caused by the sags and quicker ageing of machines.

To illustrate that the outcome of a voltage sag case study depends highly on the location, reference [2] describes a case study of Electrotek Concepts at a plastic extrusion plant. The plant was suffering from an average of 15 process interruptions per year. In this case, restructuring the network was not possible. Protecting the machine controls and winders turned out to be the cheapest option.

CONCLUSION

Based on the case study of a Belgian textile plant, this section provided guidelines on how to perform a voltage sag case study. Information has to be collected on the production process, its immunity against sags, the financial loss due to a process interruption and data on the annual number of sags. Once this information has been gathered, possibilities to reduce outage costs can be investigated. These possibilities can be classified into three groups:

1) Within the process itself
2) Between the process and the grid
3) Within the grid

Immunization between the process and the grid can be applied in every situation, whereas immunization possibilities within the process or within the grid have to be studied separately in each case.

In our case study, it turned out that immunization options within the process were not possible. Immunization options between the process and the grid appeared to be too expensive and a restructuring of the network was the only financially viable option. In a different case study of a plastic extrusion process, performed by Electrotek Concepts, the protection of the controls and winders turned out to be the most cost-effective solution.

From the above case studies, and the subsequent discussion with extrusion machine manufacturers, we could draw the following additional conclusions:

1. Standard products from extrusion machine manufacturers have hardly any sag immunity beyond the legal binding regulations.
2. Retrofitting textile extrusion lines after their installation is sometimes possible. Therefore, we recommend users of textile extrusion machines to contact their electricity supplier and/or the network operator about the number and characteristics of sags over the past few years. Based on this information, they can install machines with the required immunity to voltage sags instead of buying ones having little or no sag tolerance.

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