Case Studies
Power Quality
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Voltage dips at an automobile manufacturer

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1 Introduction

Various departments at a car manufacturing plant are suffering from regular process outages due to voltage dips. These dips are causing production losses in the Metal Operation, Spray Coating, and Assembly departments that directly affect the productivity of the plant. The cost of those losses is directly related to the profile of the voltage dip (duration and depth).

1.1 Voltage dips

A voltage dip is a short (from milliseconds up to seconds) decrease of more than 10 per cent of the supply voltage, but without the supply voltage disappearing completely (Figure 1)

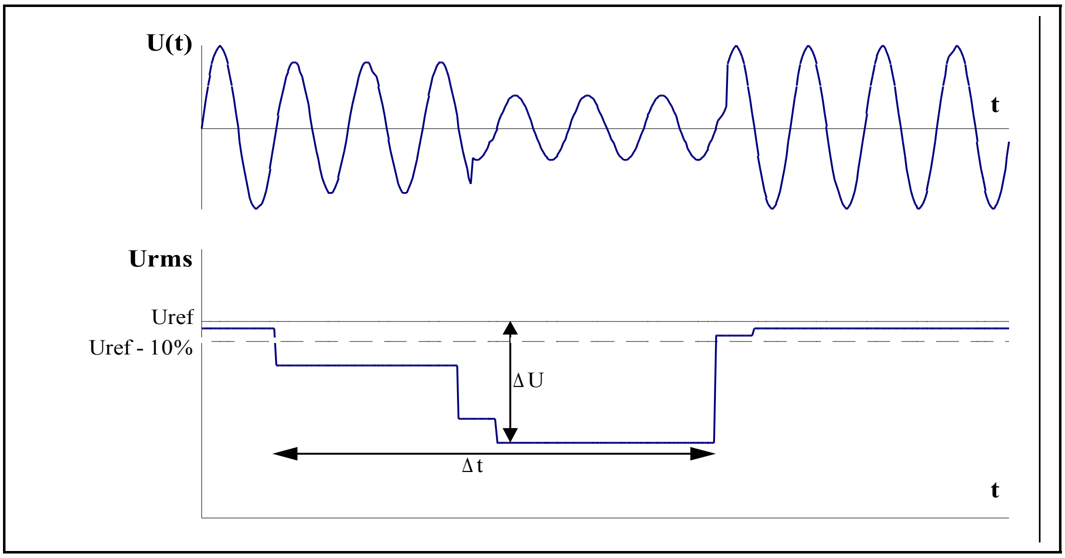

Figure 1 Voltage signature (top) and RMS-values (bottom) during a dip

Dips originating from short circuits are inherent in the exploitation of an electricity grid.

In a radial network, a voltage dip caused by a short circuit can be calculated as follows. Assume $\underline{Z}_F$ is the impedance between the short-circuit point and the point of common coupling (Pcc) (Figure 2). $\underline{Z}_B$ is the 'source impedance' between the Pcc and the high voltage grid. $\underline{Z}_B$ is also called 'short-circuit impedance'. If the voltage $\underline{E}$ is considered constant during the short-circuit, the voltage decrease at Pcc (and thus also at all other feeders) can be calculated as follows:

$$\underline{U}_{dip} = \frac{\underline{Z}_B}{\underline{Z}_F + \underline{Z}_B}\underline{E}$$

The voltage decrease is larger if the fault location is closer to the Pcc.

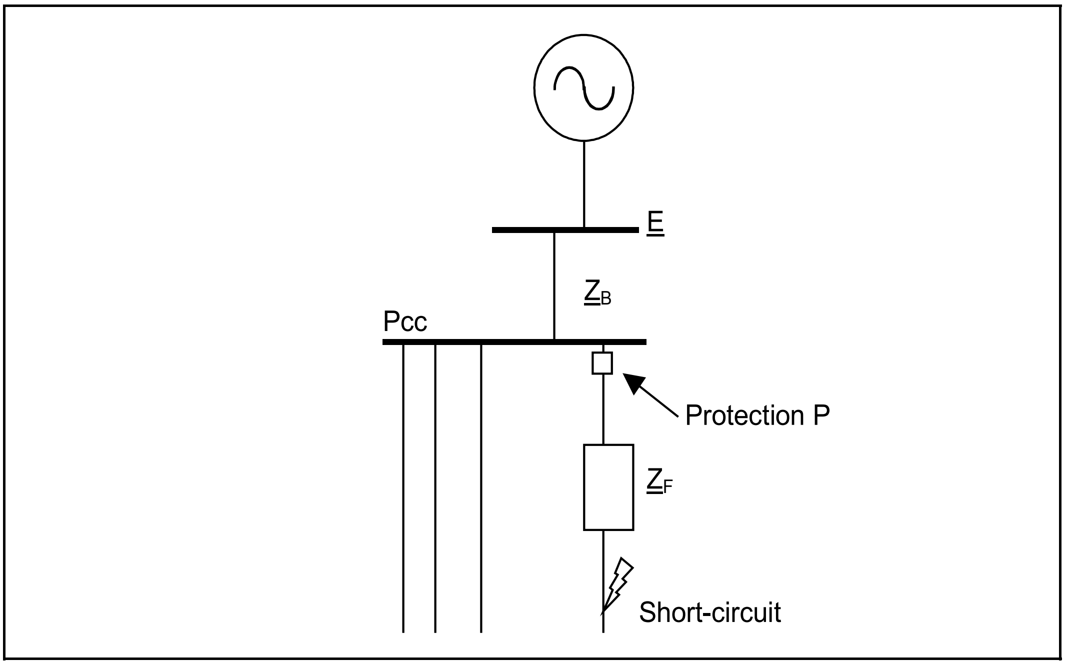

Figure 2 Voltage dip caused by a short-circuit

The same principle also applies to meshed grids. Because the calculation for a meshed grid is more complex, a load-flow calculation is usually used.

The number of distorted fases highly depends on the voltage level at which the short-circuit occurs. Most faults on overhead lines are single-phase. These include, for example, faults over insulators or to nearby structures. In underground distribution systems, multiple-phase faults can occur as well. Examples include faults resulting from digging or faults in cable sleeves.

The duration of a dip depends on the time between the fault and the clearance of the fault by the protection equipment (P in Figure 2). This time is in most cases determined by the selectivity delays of the protection devices.

2 Problem description

Over a five year period, the automobile manufacturer experienced an average of three process interruptions per year due to external voltage dips. The accumulated cost reported during these five years was approximately one million euro, or an average of € 60,000 per interruption.

Department	Yearly costs
Metal operation	€ 10 000
Spray coating	€ 90 000
Assembly	€ 80 000

Table 1 Average annual cost due to voltage dips (by department)

Table 1 shows the average annual cost due to voltage dips by department. We will investigate the cost to the Spray Coating and Assembly departments in greater detail.

2.1 Costs process interruptions at the Spray Coating department

The plant contains three almost identical spray-coating lines for primer and finish lacquering. The spray coating process is controlled by various PLCs, which are vulnerable to dips. There are also several large fans that condition the spray cabins. These fans can be interrupted for up to 20 seconds without causing significant losses. However, voltage dips often result in longer interruptions of the fans, causing major losses.

2.2 Cost of process interruptions at the Assembly department

In the Assembly department, the primary losses caused by voltage dips are production delays. During standard production conditions, a car leaves the assembly process every 65 seconds. This is called the ‘typical time’. In case of a production delay of one typical time, one car less is delivered, meaning that about €1,800 cannot be charged through.

Four years of monitoring showed that dips causing interruptions in the assembly process last on the average 20 typical times, resulting in an average loss per process interruption of 20 x €1,800 = €36,000.

2.3 Analysis of the grid connection

The plant is fed by two cables connected to a medium voltage station. The medium voltage station includes two bus bars, which are interconnected under normal conditions. The bus bars are connected to the high voltage grid via three transformers (see Figure 3).

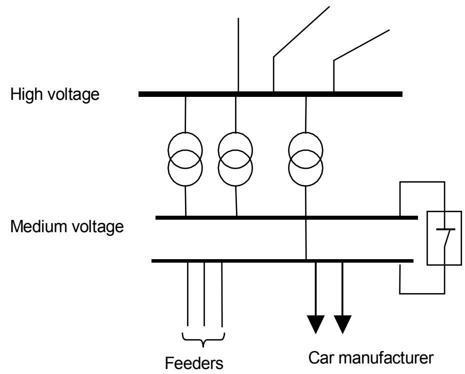

Figure 3 Grid topology of the connection to the car manufacturing plant

Several other feeders are also connected to the same medium voltage bus bars. Most of those feeders supply the local distribution grid.

2.4 Analysis of the monitoring data

A Power Quality analyzer has been installed at the plant. It accurately stores all dip events (length plus depth) and creates a DISDIP table. The characteristics of the voltage dips that caused specific interruptions can be extracted from these data.

2.4.1 Total number of dips

The electricity grid feeding the plant has a structure that is similar to other medium voltage stations feeding underground power cables. As a consequence, the voltage quality is also comparable. In such an electricity grid, the number of three-phase dips with a decrease of more than 20 per cent of the nominal voltage (the typical sensitivity of industrial processes) lies between 0 and 6 per year. In the monitored years, the number of dips at the plant averaged three per year, which is within the range of the number that can normally be expected.

2.4.2 Evolution of the number of dips

Evolutions in the dip data can be assessed by a regular calculation of the Non Quality Factor[1] (NQF). Non Quality Factor calculations have only been initiated recently for this plant, so it is too early to determine if the voltage quality is increasing or decreasing.

3 Relation between dips and process interruptions

Experience has shown that two levels of sensitivity can be distinguished for the majority of industrial processes:

- A sensitivity to one-, two-, and three-phase dips. In this case, the origin of most process interruptions can be found in single phase connected electronics (like PLCs or PCs) or in VSDs with a very small capacitor on the DC-bus
- A sensitivity for three-phase dips only. In this case, the origin of process interruptions can be found mainly in the VSDs.

The plant seems most sensitive to three-phase dips. Figure 4 shows the duration and depth of three-phase dips at medium voltage and the related financial losses.

[1]When calculating the Non Quality Factor, every dip is given a weighting factor, according to the IEC 61000-2-8 standard. Deeper and/or longer dips are given a higher weighting factor. The weighted sum of the dips over a certain period of time is called the Non Quality Factor.

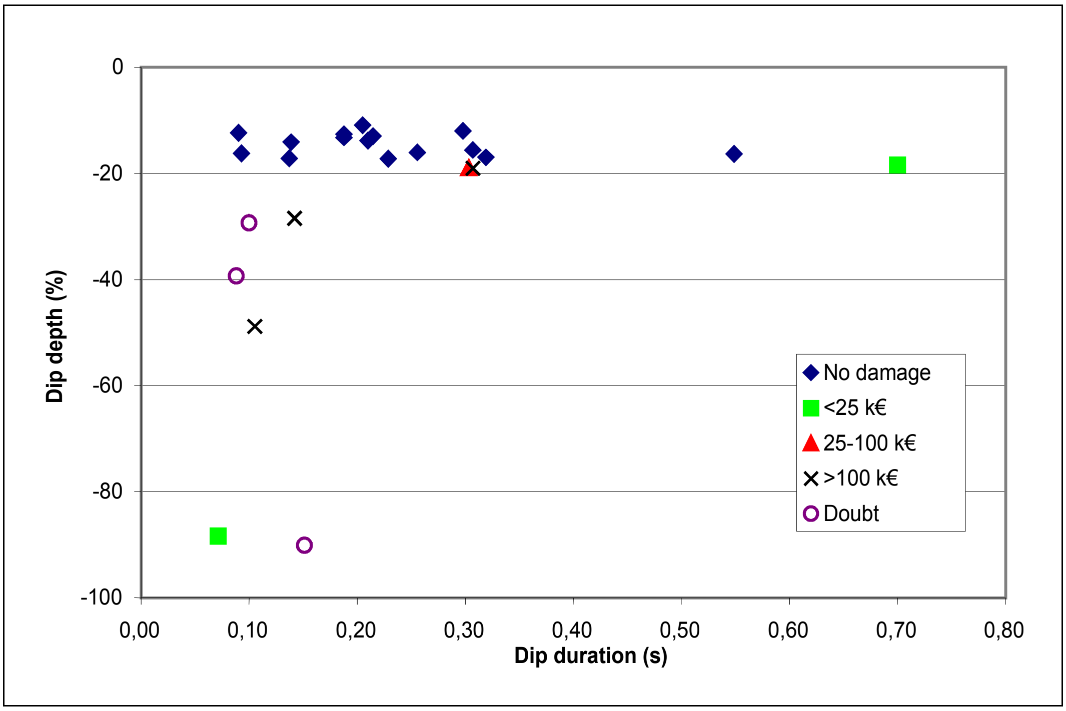

Figure 4: Three phase dips and related production losses for the car manufacturer between 2003 – 2005

The above figure shows that the automobile manufacturer is sensitive to dips with a depth of more than 18 per cent.

4 Immunisation options

Figure 5 shows a schematic overview of the possibilities for protecting processes against voltage dips.

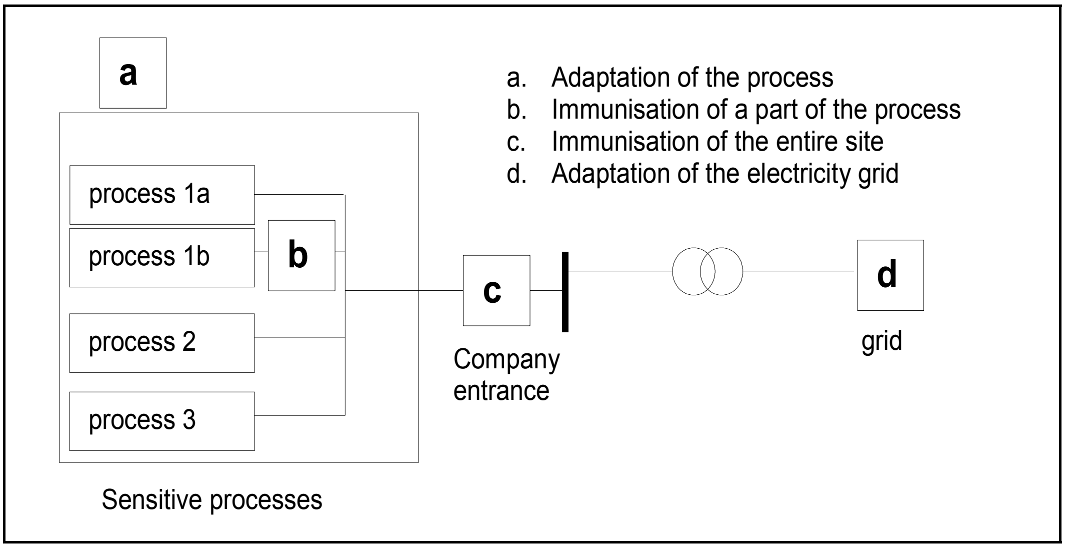

Figure 5: Schematic overview of immunization options

The four categories in this figure are investigated for the spray coating process and assembly process.

4.1 Adaptation of the process

4.1.1 Spray coating process

The large fans used to condition the spray coating cabins are equipped with a 'restart on the fly' system. This system ensures that the number of revolutions, which is decreasing during a dip, is automatically brought back to the nominal value after the nominal voltage has been restored. This system avoids the need of manual intervention and protects the equipment against voltage dips with durations of up to 500 milliseconds.

4.1.2 Assembly process

The assembly process contains various electrical users, many of which are sensitive to voltage dips. The immunization of these electrical users is not discussed in this case.

4.2 Immunisation of parts of the process

For the assembly process we investigated if the immunization of several users against voltage dips would be cost-efficient. We analysed which users create a bottleneck in the event of a restart after a voltage dip. Figure 6 shows a schematic overview of the assembly department.

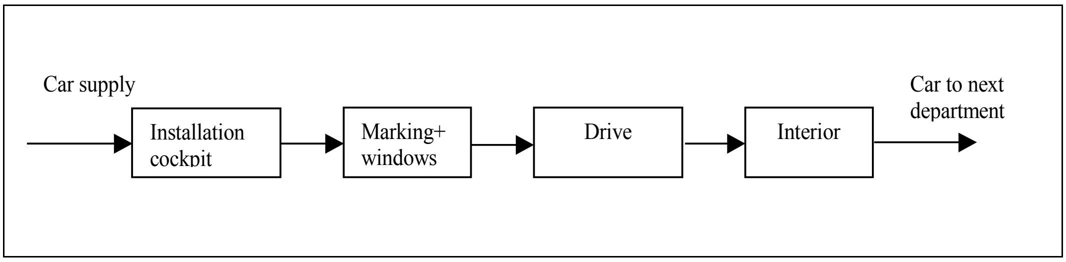

Figure 6: Schematic overview of the assembly process

The following bottlenecks were identified:

- 'Drive' sub-process: in this sub-process (see Figure 6), the motor and other large parts and components are placed in the bodywork. After a dip with a process interruption, this sub-process is the bottleneck for restarting. According to the car manufacturer, restarting this process accounts for 70 per cent of the costs due to a voltage dip at the assembly department. Since this sub-process contains various users, the entire process needs to be immunized. The total process power is 400 kVA.
- 'Installation cockpit' and 'Marking and installation windows' sub-processes (see Figure 6):
    - Cockpit installation. Restarting the manipulators and glue guns takes about 15 minutes. The power of these users is about 10 kVA.
    - Marking. This process has a total power of 15 kVA.
    - The various chains on which the cars are transported require a total of 15 kVA.

- Other users. There are other users that are interrupted during a dip. While they can all be restarted quickly, this process nevertheless takes a few minutes. To minimize the interruption time, the car manufacturer has made a priority list of which user to start up first.

Table 2 shows the users that need to be protected in the assembly process with an estimation of the possible cost reduction.

	Sub-process	Power	Potential cost reduction, as a percentage of the total cost of voltage interruptions for the assembly line
1	Drive	400 kVA	70%
2	- Cockpit - Marking - Circuit one transport chain	40 kVA	15%
3	Other users	> 1 MW	15%

Table 2 : Summary of the users that need to be protected in the assembly process, and the potential cost reduction

In the following sub paragraphs, we will discuss the protection of these users against:

1. All dips (§4.2.1.1)
2. Most dips (§4.2.2.2)

4.2.1 Immunisation against all dips

Protection against all dips can only be accomplished by using Uninterruptible Power Supplies (UPS) or a flywheel (see Figure 7).

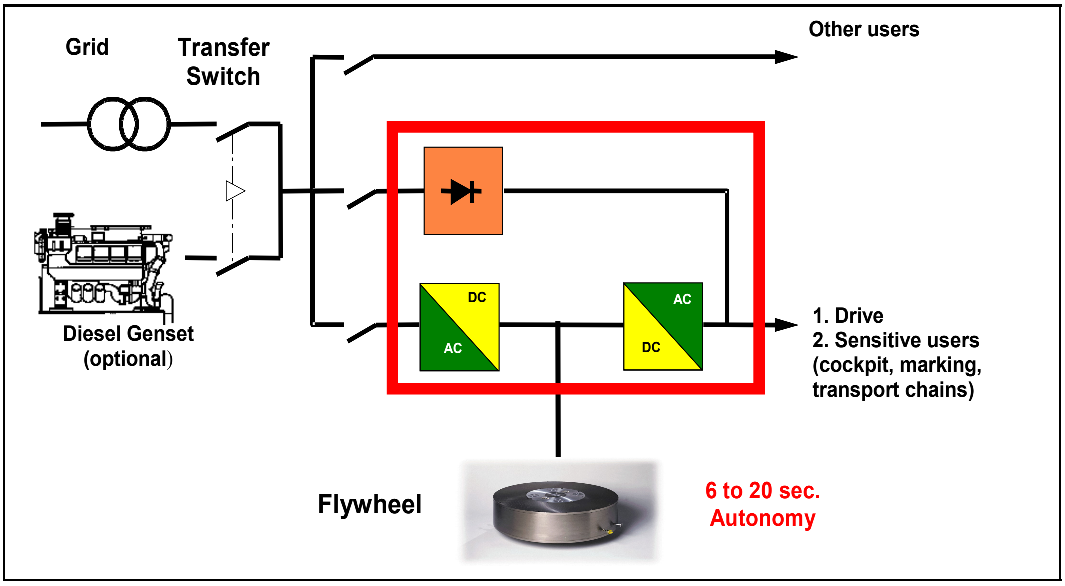

Figure 7: Using a flywheel for protecting sensitive sub-processes

Table 3 shows the cost for protecting the assembly process by a static UPS or a flywheel.

	400 kVA (Drive)	40 kVA (Cockpit, Marking, Transport chain)
Static UPS	€ 90 000 + 15% annually	€ 15 000 + 15% yearly
Flywheel	€200 000 + 5% annually	not applicable

Table 3: Cost of measures for protecting sensitive sub-processes against all dips

It can be concluded from this table that only a UPS protection system is a useful option.

4.2.2 Protection against most remaining dips

Protection against the most frequently occurring dips can be accomplished by using a Dynamic Voltage Restorer (DVR). The DVR, which is installed in series between the grid and the line (see Figure 8), calculates what percentage of the voltage is missing during a dip and adds this percentage via a transformer.

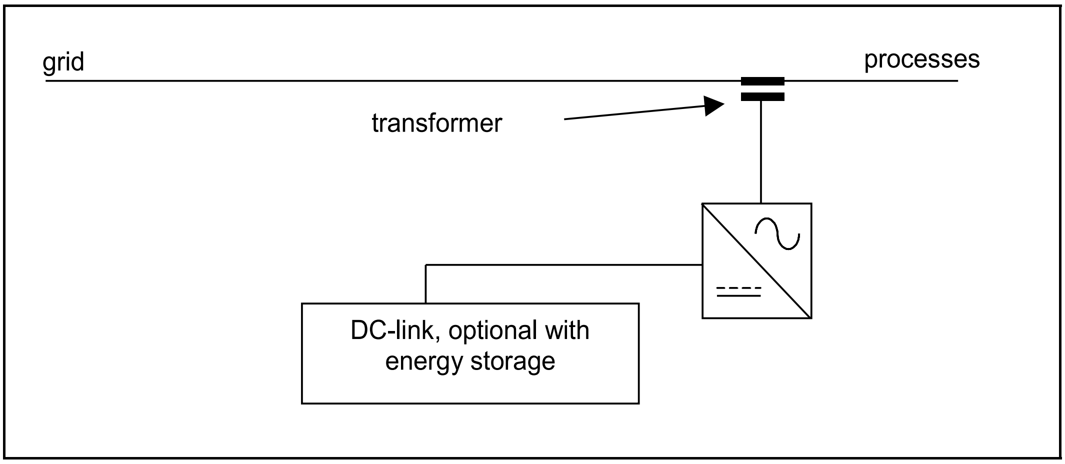

Figure 8: Dynamic Voltage Restorer (DVR)

The maximum percentage that a DVR can add to the voltage is limited; a typical value is 30 per cent. Figure 9 shows the resulting immunity of the assembly process equipped with a DVR. It shows that the process is now immune against dips with depths of up to 48 per cent.

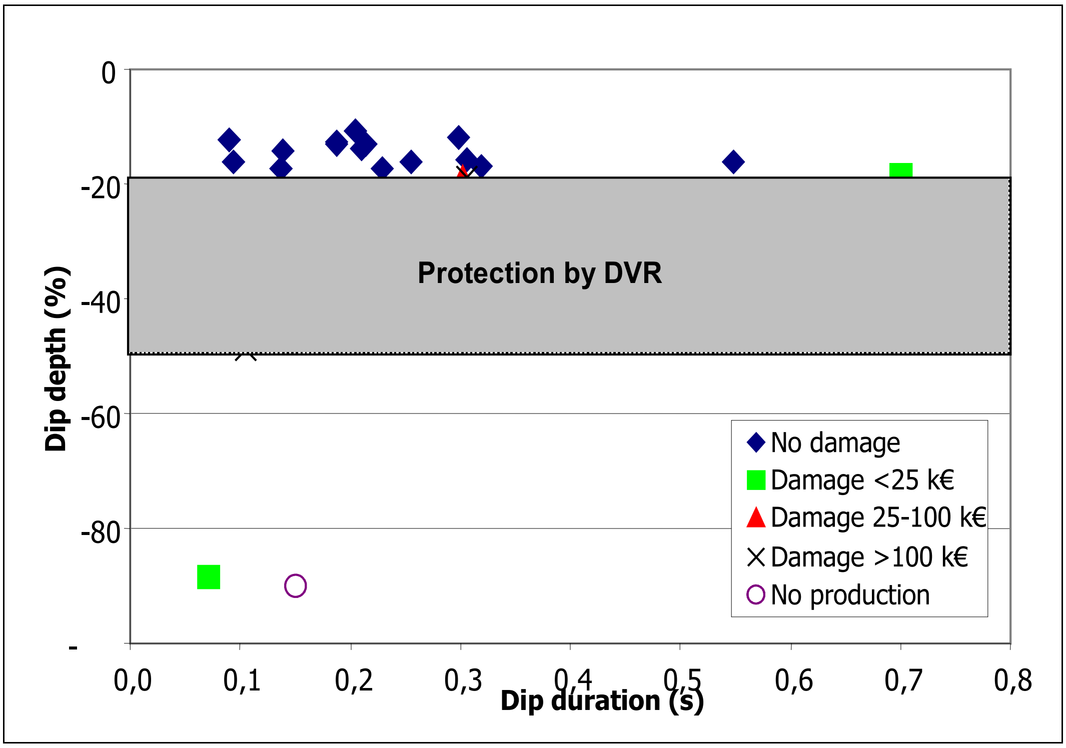

Figure 9: Immunity of the assembly process after adding a DVR

Experience has shown that a DVR can avoid 2/3 of all interruptions due to voltage dips. For the car manufacturing plant, 70 per cent of all losses reported in the last three years could have been avoided by a DVR.

The cost of a DVR (installation included) is €45,000 for the ‘Drive’ sub-process, and €7,000 for the Cockpit and Marking processes and the Transport chain. Unlike the flywheel system, the standby and maintenance cost of a DVR is negligible.

4.3 Protection of the entire site

Due to its high total power demand, immunizing the entire factory is not a cost-effective option.

4.4 Adaptation of the electricity grid

Adaptations in the electricity grid can have an influence on the number and type of voltage dips that occur. A direct connection to the high voltage grid, for example, could result in fewer dips for the plant. A first estimate however showed that investing in such an adaptation would not have an acceptable pay-back rate for the automobile manufacturer.

4.5 Summary

Table 4 summarizes the costs and revenues of the different options, assuming that the future frequency of dips and process interruptions is the same as in the period monitored. The last column shows the payback time of the different options.

nr	Description	Investment	Annual costs	Annual revenues	Payback time
1	Protection of ‘Drive’	€ 100 000	€ 15 000	€ 50 000	2,5 years

	process with static UPS				
2	Protection of 'Drive' process with DVR	€ 50 000	0	€ 35 000[2]	1,5 years
3	Protection of 'Drive', 'Cockpit', 'Marking', and 'Transport chain' process with static UPS	€ 115 000	€ 17 500	€ 60 000	2,5 years
4	Protection of 'Drive' 'Cockpit', 'Marking' and 'Transport chain' process with DVR	€ 55 000	0	€ 40 000	1,4 years

Table 4: Summary of the cost and revenues of the different scenarios

The payback time is often used in industry to evaluate the profitability of an investment. The Net Present Value however provides a more relevant evaluation tool. For calculating the Net Present Value, all costs and revenues are charged over the total lifetime of the investment and then calculated back to time t = 0 by using a discount rate. The project is profitable if the sum of the discounted revenues is higher than the sum of the discounted costs.

We carried out a simple analysis in this case, assuming a five year lifetime of the investment and a discount rate of 0 per cent. The cost of this project is the write-down of the immunization equipment (immunization cost). The revenue of the project consists of the reduction of the Non Quality Cost (= the former cost of process interruptions, minus the remaining cost of process interruptions).

Table 5 shows the resulting values for the calculated scenarios.

nr	option	Remaining Non Quality Cost Assembly	Immunization costs
now	now	€400,000	€0
1	Protect process 'Drive' with static UPS	€120,000	€165,000
2	Protect process 'Drive' with DVR	€200,000	€50,000
3	Protect 'Drive', 'Cockpit', 'Marking', and 'Transport chain' processes with static UPS	€60,000	€200,000
4	Protect 'Drive', 'Cockpit', 'Marking', and 'Transport chain' processes with DVR	€155,000	€55,000

Table 5: Summary of the immunization costs and remaining costs due to voltage dips calculated over five years (using today's number of process interruptions)

Figure 10 shows a table summarizing the costs over a five-year period[3], consisting of a Non Quality Cost (cost due to process interruptions) and an immunization cost.

[2] The values result from the decrease in interruption costs. The 'Drive' sub-process represents 70 per cent of the interruption costs of the complete assembly department, which total €75,000. A DVR can reduce this cost of interruptions at the 'Drive' sub-process by 70 per cent. This results in a decrease in interruption costs of approximately € 35,000 (€ 70,000 x 0.7 x 0.7).

[3] Five years is seen as the minimal lifetime of an installation in an industrial process.

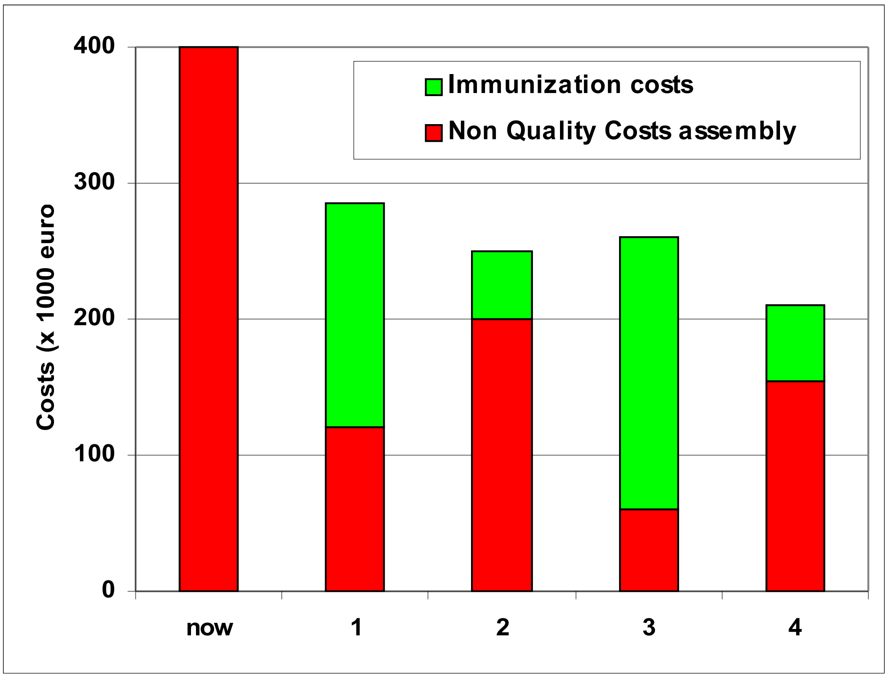

Figure 10: Summary of the immunization cost and remaining cost due to voltage dips for the assembly process, calculated for a five-year period (using the current number of process interruptions)

Both the payback time and the Net Present Value are optimal for the scenario in which a DVR protects the 'Drive', 'Cockpit', 'Marking', and 'Transport chain' processes. The payback time for this solution is 1.4 years.

5 Conclusions and recommendations

In this case study we investigated the options to reduce the costs caused by voltage dips at an automobile manufacturing plant, with particular emphasis upon the Spray Coating and Assembly departments. The following conclusions can be drawn:

1. The number and type of dips occurring at the point of connection of the plant is regular. It is similar to what is monitored at other medium voltage stations that have the same grid structure.
2. A detailed analysis of the spray coating process reveals that installing a 'restart on the fly' system on the large conditioning fans substantially reduces the related voltage dip losses.
3. A detailed analysis of the Assembly department shows that there are two main bottlenecks that determine the restart time after a dip (the 'Drive' sub-process and the 'Cockpit', 'Marking', and 'Transport chain' users). These bottlenecks can be removed by installing a Dynamic Voltage Restorer (DVR), which results in a payback time of 1.4 years.