CONSIDERATIONS FOR CHOOSING THE APPROPRIATE VOLTAGE SAG MITIGATION DEVICE

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This paper compares various systems protecting industrial processes against voltage sags (Flywheel, Static UPS, Dynamic Voltage Restorer, Statcom, Shunt connected Synchronous Motor, Boost Converter, Active Front End and a Transformerless Series Injector). The systems are compared with regard to dip immunization capability and several other technical and economic parameters.

1. Introduction

A voltage sag is a decrease of the supply voltage between –10 and –99% during a short time (<2s). Sags are known to be among the most costly Power Quality phenomena in industry. In theory, installing an Uninterruptible Power Supply (UPS) is the easiest way to protect sensitive processes against all sags. However, due to their considerable purchase and maintenance cost, UPS's are only installed on a structural basis in places where the damage resulting from power supply problems are very high such as in hospitals, computer facilities and financial institutions. In other cases, including most industrial processes, the installation of protective equipment must be subjected to a cost-benefit analysis, often showing that installing a UPS is too expensive.
Triggered by problems in industrial processes containing variable speed drives, solutions to protect equipment against voltage sags are now commercially available. Due to the wide variety and exotic vender specific names of these systems, it is not straightforward to choose the optimal techno-economic solution for a given problem.
This paper analyses differences between a number of systems that can be installed in existing processes showing problems with voltage sags. Taking into account sag statistics from various countries, the paper provides guidance in the effectiveness (percentage of process outages prevented) that can be expected by installing these systems.
Firstly, this paper describes the equipment that is analysed. Subsequently the sag immunization capability and other technical and economic aspects are evaluated.
Taking into account the performance of the described systems with regard to these aspects, the paper finally gives guidelines for practical situations.

2. Types of mitigation equipment

2.1 Flywheel

A flywheel together with a motor-generator (M/G) set can immunize critical processes against all voltage sags. When a voltage sag occurs, the motor-generator set feeds the load, the energy being supplied by slowing down the flywheel. Different connection topologies of the flywheel to the M/G-set exist of which Figure 1 shows the main components of a connection using power electronics.

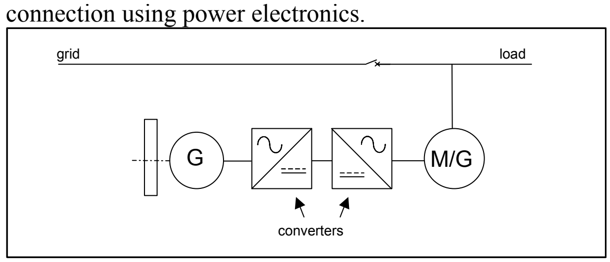

Figure 1 Flywheel

2.2 Static UPS with minimal energy storage

Figure 2 shows the main components of a Voltage Frequency Independent (VFI) or online variant of a static UPS, which containis energy storage only to protect against short time electricity disturbances. If a sag occurs, the load is fed by the battery through the DC/AC converter.

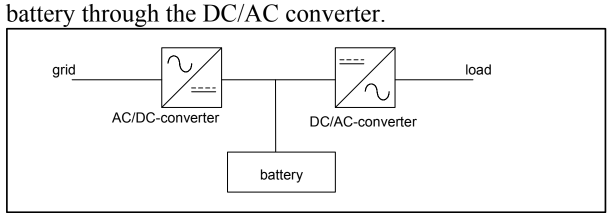

Figure 2 Voltage Frequency Independent static UPS

2.3 Dynamic Voltage Restorer (DVR)

A Dynamic Voltage Restorer (DVR) [3] remains connected to the grid during a voltage sag and calculates the missing part of the voltage. It adds this missing voltage through a transformer, installed in series with the load. Depending on the concept, the energy to feed the load during a sag either originates from the network or from an additional energy storage unit (mostly capacitors). The paper describes two concepts by different manufacturers.
The first (hereafter called DVR-1) does not contain energy storage and is continuously on-line. It is commercially available with a voltage lifting capability up to 50%. The

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version with a lifting capability of 30% will be analysed in chapter 3, since this version is considered to be the most cost effective by the manufacturer.

The second (Figure 3, hereafter called DVR-2) containing energy storage aims at large loads. The amount of MW to be injected can be chosen; the lifting capability depends on the load. A 2 MW unit can boost the voltage of a 4 MW load by 50% or the voltage of an 8 MW load by 25%. In contrast with most other devices, the energy storage capacity is an issue riding through longer sags.

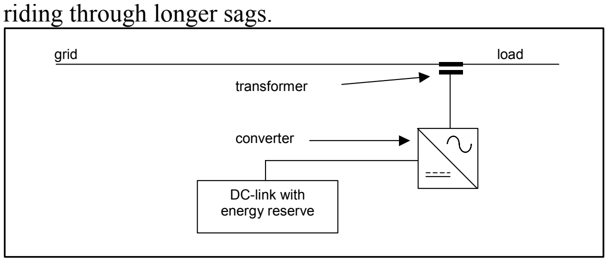

Figure 3 Dynamic Voltage Restorer (DVR-2)

2.4 Statcom

A statcom [3] is a current injector connected in parallel (shunt) with the load. A statcom can mitigate voltage sags by injecting reactive power into the system. The sag mitigating capability can be enlarged by adding energy storage such as Superconducting Magnetic Energy Storage (SMES)[6].

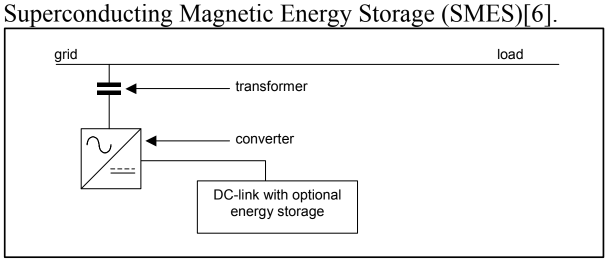

Figure 4 Statcom

2.5 Shunt connected synchronous machine

A shunt connected synchronous machine has some similarities with the Statcom, but does not contain power electronics. The capability of the synchronous machine to supply large reactive currents enables this system to lift the voltage by 60% for at least 6 seconds. Next to this, a small flywheel protects the load against full outages of 100 ms, which will not be considered in chapter 3.

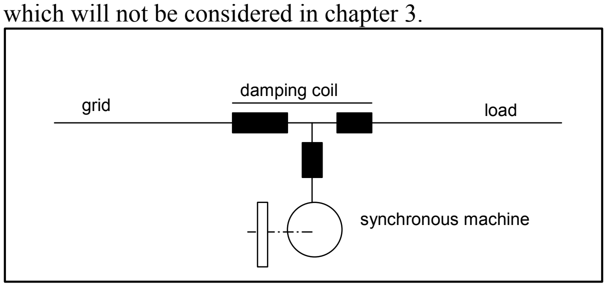

Figure 5 Shunt connected synchronous machine and flywheel

2.6 Boost Converter

A boost converter is a DC-DC converter boosting the voltage of a DC-bus (e.g. of a Variable Speed Drive) up to the rated level (Figure 6). The largest sag that can be compensated depends on the current rating of the boost converter. The boost converter is activated as soon as the voltage sag is detected at the DC bus of the application [7]. Next to the capability of immunization against symmetrical sags of –50%, the boost converter can handle deeper unsymmetrical sags such as a complete outage of one phase, which will not be taken into account in chapter 3. To protect against complete outages the boost converter can be expanded with batteries.

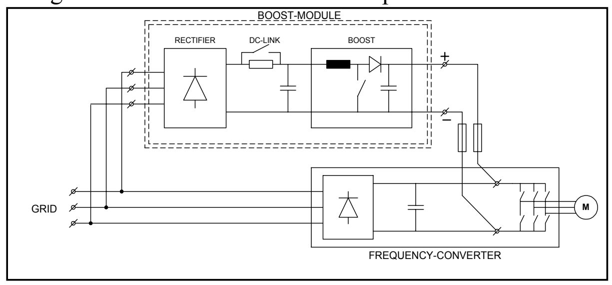

Figure 6 Boost converter

2.7 Active Front End

An Active Front End (AFE, Figure 7) [4] is a converter that may operate as a rectifier, while using IGBT's instead of diodes. The AFE can maintain a constant DC voltage during a voltage sag. The current rating of the AFE determines the maximum sag that can be corrected.

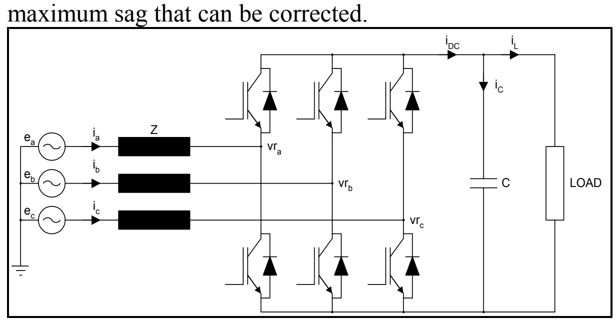

Figure 7 Active Front End (AFE)

2.8 Transformerless series injection

At the occurrence of a voltage sag, the static switch of this series injection device (Figure 8) is opened and the load is supplied by an inverter. The power to the DC bus of the inverter is maintained by charging two capacitors connected in series. For sags with 50% remaining voltage, the rated voltage can be supplied to the load. Next to this, optional energy storage (capacitors) can mitigate a complete outage for a limited time duration, which will not be taken into account in chapter 3. Also its capability to handle deeper unsymmetrical sags, such as a complete outage of one phase will not be taken into account in the evaluation.

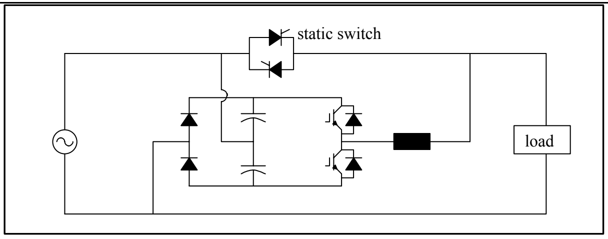

Figure 8 Transformerless series injection

3. Dip immunization capability

This chapter compares the above described systems with regard to dip immunization capability. More concretely it analyses *the percentage of outages due to voltage sags that will be mitigated*. Three important parameters are required to conduct a proper analysis; they are described in sections 3.1-3.3 and summarized in section 3.4.

3.1 Relative frequency of sags with a certain depth.

The frequency of sag occurrence is different for each grid location. Figure 9 shows the percentage of sags less than a certain voltage drop in %. The following statistics are used:

B1, B2 : Two MV bus bars in Belgium
F : MV bus bar in France
NL : MV bus bar in The Netherlands
US : DPQ Study in the US [1]
C : Average of MV bus bars in Cigre report [2]

The duration of the sags is not mentioned since it is assumed that all systems are able to function for at least the maximum 2 s of a sag. The relative distribution shown in figure 8 is assumed to be representative for all types of sags (1, 2 or 3 phases). Point P in this figure indicates for example that 47% of the sags in the CIRED (C)-statistics have a voltage drop less than 20%.

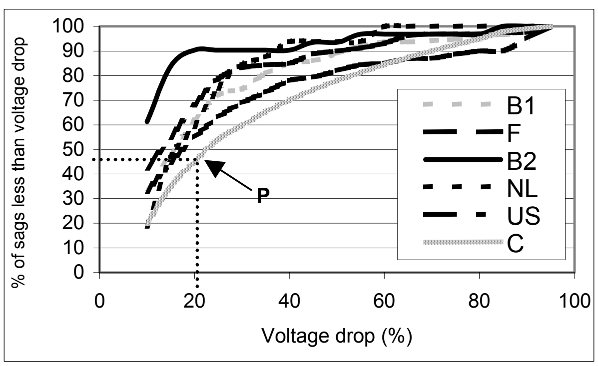

Figure 9 Sag statistics from different countries, showing the percentage of sags less than a certain voltage drop in %

3.2 Immunization level

Three different concepts to enhance the immunity against voltage sags can be distinguished.

a) Load is supplied by an external energy source

These types of systems (flywheel, static UPS) can immunize against all voltage sags. The time duration of the maximum immunization only depends on the amount of energy stored.

b) The voltage is lifted by a certain percentage

These systems (Statcom and DVR) use the remaining voltage in the grid as a starting point and add the missing voltage. If they cannot add the entire voltage, they use their maximum capability. A sag is considered to be mitigated if the final voltage (grid voltage during sag plus added voltage) is high enough to maintain normal operation of the load.

c) The load is supplied by the grid, even during a sag

In order to retain a constant power flow to the load, these types of systems (AFE, boost converter and transformerless series injection) compensate the decreased voltage by drawing a higher current from the grid. Therefore, the maximum sag depth that can be compensated depends on the current rating of the system.

3.3 Sensitivity of the process

It is often overlooked that the initial sensitivity of a process may have an impact on the percentage of outages mitigated by protective equipment. However, this is of major importance when comparing systems within category b) and c) of section 3.2 as illustrated in Figure 10.

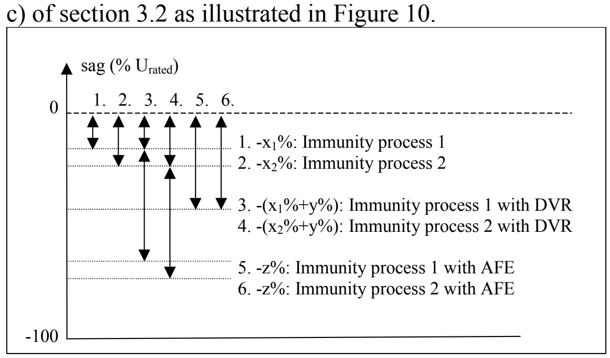

Figure 10 Immunity of processes with different initial immunity with and without additional immunization equipment

Equipment in category b) will lift the voltage by a certain percentage. If a process being immune to sags of –x% is equipped with an system of category b), such as a DVR having a voltage lifting capability of +y%, the process is be immune to voltage sags of –(x%+y%).

On the other hand, equipment in category c) will immunize the process against sags of a predefined level (e.g. z%). By installing equipment of category c) the percentage of reduced outages is less if the initial immunity of the process was –30% in comparison to an initial immunity of –10%.

3.4 Summary

Table 1 shows the percentage of outages due to voltage sags that can be reduced by the described systems using sag statistics from the CIGRE report and one Belgian bus bar (C and B2 in Figure 9) and taking into account two different levels of initial immunity of the process (-10% and –30%). The percentage of prevented outages is not affected whether the protected equipment is only vulnerable to 3-phase sags or to 1, 2 and 3 phase sags since the paper assumes that:

- The relative distribution of the sags depth is equal for all sags (1, 2 and 3 phase).
- All protective equipment provide the same relative

protection for these sags.

Percentage of outages due to sags that will be reduced: 40 - 60% 60 - 80% 80 -100%	Output (AC/DC)	Concept of immunization (section 3.2)	Maximum voltage drop being protected in %	Maximum voltage lift in %	'Cigre bus bar' (C), initial immunity –10%	'Cigre bus bar' (C), initial immunity –30%	Belgian bus bar (B2), initial immunity –10%	Belgian bus bar (B2), initial immunity –30%
Flywheel	AC	a	100	/				
Static UPS	AC	a	100	/				
DVR-Cap1	AC	b	/	30				
DVR-Cap2, 200% load	AC	b	/	50				
DVR-Cap2, 400% load	AC	b	/	25				
Statcom-SMES	AC	b	/	60				
Shunt Connected SM	AC	b	/	60				
Boost Converter	DC	c	50	/				
Boost Conv.200% derated	DC	c	80	/				
Boost Converters + batteries	DC	c	100	/				
AFE, 25% derated	DC	c	50	/				
AFE, 200% derated	DC	c	80	/				
Transformerless series injection	AC	c	50	/				

Table 1 Percentage of outages reduced by installing different mitigation devices taking into account different sag statistics and different initial immunity of the processes.

4. Other technical and economic aspects

Sections 4.1-4.8 describe the aspects considered, while section 4.9 summarizes the performance of the analysed equipment with regard to these aspects. It should be noted that these aspects refer to products being currently available on the market.

4.1 Size

Some systems are currently available in sizes larger than 1 MW (-) while others are sold in sizes smaller than or equal to 100 kW (+).

4.2 Purchase cost

Since the decision of buying mitigation equipment to prevent damage due to voltage sags is the outcome of a cost-benefit analysis, the purchase price of the system is very important. Although contracts are made on individual basis and can vary substantially, this paper provides rough guidelines for the purchase and installation cost of a medium sized (between 100 kVA and 500 kVA) device if available. Three price categories are defined:

- : > €250 per kVA
= : €150-250 per kVA
+ : < €150 per kVA

4.3 Maintenance

Depending on the type of system, the maintenance costs may be substantial. This paper only distinguishes whether annual maintenance is required (-) or not (+).

4.4 Efficiency

Many systems require continuous electricity demand due to the use of power electronics, the use of moving parts (flywheel) or cooling (SMES) resulting in a reduction of the overall efficiency. This paper distinguishes three categories:

+ : losses <0,5% S_{rated}
= : losses 0,5-2% S_{rated}
- : losses >2% S_{rated}

It should be noted that a low efficiency has high implications on the economic decision making process. Taking into account an electricity rate of €0,05/kWh and an efficiency of 97%, the annual loss per installed kW is 8760 h/a x 0,05 €/kWh x 0,03 = 13,1 €.

Considering an interest rate of 10%, the discounted losses in 10 years per kW will be €80,4.

4.5 Reaction time

Some of the protection devices need to detect the voltage sag before they can react. This may results in a transient process behaviour.

The reaction (activation) time of the protective device is divided into three categories:

+ : reaction or activation transient < 1 ms
= : transient 1-5 ms
- : transient > 5 ms

4.6 Voltage harmonics

Some of the mitigation systems are also able to continuously compensate for voltage harmonics originating from the supplying network (+) while others do not influence voltage harmonics (=).

4.7 Current harmonics

If the downstream load contains many power electronic applications, such as variable speed drives, the current will be highly non-linear. Some voltage sag mitigation systems have the ability to draw a linear current from the network despite of the non-linear loads (+) while others do not influence current harmonics (=).

4.8 Reactive power

Some applications have the ability to supply or draw reactive power continuously (+) while others cannot (=).

4.9 Summary

Table 2 summarises the performance of the described systems with regard to these parameters:

	Size	Purchase cost	Maintenance	Efficiency	Reaction time	Voltage harmonics	Current harmonics	Reactive power
Flywheel	+	-	-	-	=	+	+	+
Static UPS	+	-	-	-	+	+	+	+
DVR-1	+	+	+	=	=	=	=	+
DVR-2, 200% load	-	-	+	-	=	+	=	=
DVR-2, 400% load	-	=	+	-	=	+	=	=
Statcom-SMES	-	=	-	=	-	=	=	+
Shunt connected SM	+	=	-	-/=	=	+	+	+
Boost Converter	+	+	+	+	+	=	=	=
Boost Converter 100% derated	+	=	+	+	+	=	=	=
Boost Converter + batteries	+	-	-	-	+	=	=	=
AFE, 25% derated	+	+	+	-	+	+	+	+
AFE, 200% derated	+	=	+	-	+	+	+	+
Transformerless series injector	+	=	+	+	=	=	=	=

Table 2 Technical and economic aspects of different mitigation methods

5. *Cost-benefit analysis of mitigation equipment*

In order to analyse whether the expected reduction in outage cost outweighs the cost of the protective equipment, the following adapted version of the Net Present Value method can be used: [5]:

$$f \cdot p_{prev} \geq \frac{C_{inv}}{C_{sag}} x \left(\frac{(1+i)^n (i + p_{mnt}) - p_{mnt}}{(1+i)^n - 1} \right) \quad (1)$$

with

C_{inv} initial investment per kVA (Table 2),

f annual outages due to sags,

p_{prev} percentage of outages being prevented (Table 1),

$f \cdot p_{prev}$ annual mitigated outages,

C_{sag} outage cost per sag per kVA,

p_{mnt} maintenance costs per kVA per year as a percentage of C_{inv},

i discount factor,

n project time(a).

By introducing 'optimistic' values for a mitigation system (e.g. C_{inv}= €100/kVA, p_{mnt}=0, p_{prev} = 100%), this formula can be used to determine whether the reduction in voltage sag losses will outweigh the cost of any of the described mitigation devices.

6. *Conclusions*

It can be concluded that there is no single system superior in all situations. However, some guidelines can be given:

- Installing a boost converter, an Active Front End (AFE) or the DVR-1 is most appropriate if processes are to be protected containing a DC-bus that can be reached from outside. The boost converter has the advantage of having negligible losses; the AFE and the DVR-1 have other capabilities such as drawing a sinusoidal supply current or the ability of supplying reactive power.
- For processes that do not have a DC-bus, in general a DVR-1 or a transformerless series injector are most cost effective. If harmonics and reactive power also cause problems, the shunt-connected synchronous motor could be considered.
- It has also been shown that the percentage of outages being prevented by a certain solution depends on different parameters and cannot be predicted without statistical data on the sags. If all sags and short interruptions have to be mitigated, the only possible solution is installing a flywheel or a static UPS.

Acknowledgements

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In addition, information is used originating from different manufacturers of the analysed equipment.