Choosing the Correct Mitigation Method Against Voltage Dips and Interruptions: A Customer-Based Approach

Dirk Van Hertem, *Student Member, IEEE*, Marcel Didden, *Member, IEEE*, Johan Driesen, *Member, IEEE*, and Ronnie Belmans, *Fellow, IEEE*

***Abstract*—Voltage dips and interruptions may cause major economic damage, not only can they create considerable loss of production (manufacturing) or data (ICT), there is also loss of market, the loss of client trust, comfort, etc. that incite energy consumers to implement certain forms of protection for their systems. However, the selection of the most cost-effective mitigation method is difficult because of the wide range in available protection devices and the mostly unknown and variable interruption cost. In this paper, the theoretical selection method is compared with the currently used selection methods in industry, showing a discrepancy between theory and practice. Using an alternative selection method, an optimal mitigation method can be found. This paper describes this method and its use by means of a practical example. The case examined is the protection of a 250 kVA installation, sensitive to voltage dips (ICT load). The proposed method makes a cost-benefit analysis of several proposed mitigation solutions resulting in an overview giving the optimal solution for a certain interruption cost interval. It enables to clearly interpret the investment costs and to compare completely different mitigation methods, only using data available to an industrial customer.**

***Index Terms*—Mitigation, power quality, technoeconomic assessment, voltage dips and interruptions.**

I. INTRODUCTION

A. *Cost of Voltage Dips and Interruptions*

Every year, voltage dips and interruptions cause major economic damage. In the U.S. alone the annual economic damage is estimated to be between U.S.$ 104 billion and U.S.$ 164 billion [1]. Currently, there are many technical mitigation solutions available on the market, some are generally used and available [e.g., static or dynamic uninterruptible power supplies (UPS)], others are only applicable in special cases (e.g., using a boost converter in the dc-bus of a variable-speed drive) and not commonly known to the nonspecialists. All mitigation methods reduce the effective number of process interruptions to a certain extent, and each comes at a cost. Difficulties arise in determining the optimal mitigation method from a techno-economic point of view which results in the lowest total cost over the lifetime of the investment. But this optimum depends on many variables.

The investment selection methods currently used in industry differ in most cases from economically sound methods available in literature. The choice for a mitigation method is in most cases based on rule of thumb or past time experiences. Service and maintenance, support, the use of standardized solutions, working with companies known to the own company, and other non or less technical requirements dictate the eventual purchase. Although a theoretical approach is not commonly used, there clearly is a need to obtain a cost-based optimal protection against voltage dips and interruptions [2], [3].

This paper provides a method integrating theoretical cost calculations and the practical needs of an industrial customer. The optimal mitigation method is calculated from a customer's perspective, using only values available to the customer.

B. *Power Quality is an Economic Problem*

A common misconception is that power quality issues are technical problems, but in fact, power quality is a techno-economic problem. For industrial customers, power quality issues are only those problems that influence the correct operation of their process in such a way that they cause a deficit in production quality or quantity. Therefore, it is vitally important to make a clear distinction between "voltage dips and interruptions" and "process interruptions caused by voltage dips and interruptions."

The total power quality cost is the addition of the process interruption costs (no production, loss of quality,...) and the cost of the protection against process interruptions. Therefore, it is important to consider the entire process when evaluating power quality solutions, with a focus on overall cost reduction. This could lead to cheap solutions such as protecting only the most sensitive devices in a large process while reducing the total power quality cost significantly.

C. *Approach*

In the following section the differences between theory and practice are studied. The net present value (NPV) method is used for the theoretical approach of the investment decision process, and the results of surveys performed within industry are used to assert the decision taking process as it is done in practice. Section III explains an alternative method to solve the

---

Manuscript received April 4, 2005; revised February 21, 2006. This project was supported in part by the K.U. Leuven Research Council (GOA/2001/04), in part by the Belgian "Fonds voor Wetenschappelijk Onderzoek (F.W.O.)—Vlaanderen," and in part by the Belgian "Instituut voor de aanmoediging van Innovatie door Wetenschap en Technologie in Vlaanderen" under the Grant GBOU Research Project.

D. Van Hertem and J. Driesen are with the Research Group ELECTA, K.U. Leuven, Leuven 3001, Belgium (e-mail: dirk.vanhertem@ieee.org).

M. Didden is with the Electrical Power Systems and Metrology Division of Laborelec, Linkebeek 1630, Belgium.

R. Belmans is with the Research Group ELECTA, K.U. Leuven, Leuven 3001, Belgium. He is also with ELIA, Brussels 1000, Belgium.

Digital Object Identifier 10.1109/TPWRD.2006.881456

selection of the optimal mitigation method. An example is used throughout the analysis.

In Section VI, the sensitivity to the validity of the available grid data is treated.

II. CONFLICT BETWEEN THEORY AND PRACTICE

A. Theoretical Approach

1) Optimal Investment: The optimal selection method for the mitigation of voltage dips and interruptions can be determined using classic theoretical means [4]. The NPV method (1) is widely accepted as the most appropriate to calculate the profitability of investments [5]

$$NPV = -C_0 + \sum_{n=0}^{n_{tot}} \frac{f_n \cdot C_{dev\_int} - C_{operating}}{(1+r)^n} \qquad (1)$$

where

C_0	investment cost
f_n	number yearly avoided process interruptions
C_{dev_int}	cost per process interruption
$f_n \cdot C_{dev\_int}$	avoided economic damage, profit
$C_{operating}$	annual operating costs, including maintenance
r	capitalization rate
n_{tot}	lifetime of the investment.

2) Availability of Data: However, for the selection of mitigation devices, (1) often cannot be used because of the uncertainty of the parameters, especially the interruption cost [6], which depends on many uncontrollable variables [7]; among others:

- point in time of the event (day—night, winter—summer...);
- economic situation;
- duration of the event;
- announced or unannounced event;
- availability of other energy sources;
- weather conditions;
- damage caused to the installation.

As an example, the variation of the interruption cost as a function of the interruption duration is treated. Fig. 1 displays four different cost scenarios as a function of interruption duration:

1) interruption costs for an installation with a high initial cost and relative low variable costs, for instance, the paper industry;
2) installation without initial costs and a high variable cost after a certain time, for instance, a poultry farm: after about 30 min, the animals will die of suffocation because of a lack of ventilation;
3) nonlinear curve with limited initial costs and high costs if the electricity is not restored before a certain time. Afterwards, the costs rises again slowly. An application of such a curve is a static UPS-protected data center;
4) typical curve for the sale of nonperishable goods: low initial cost as sales will be postponed; on the long term, the costs increase due to the loss of client confidence (e.g., railway companies).

Using this method, the process interruption cost is crucial to examine the profitability of different investments. Since this value is situation and case dependent, the theoretical method is rarely useful in practice.

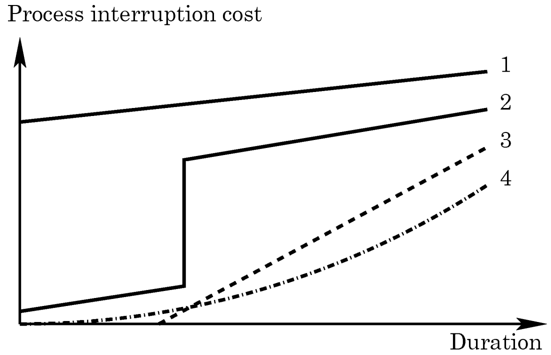

Fig. 1. Interruption cost of a device as a function of interruption duration.

B. Practice

The selection of a suitable mitigation method for a given power quality problem in industry is not based on certain rules, but case dependent. In order to obtain an overview of the current situation in industry, surveys were performed in several companies from different industries known for their sensitivity to voltage dips and interruptions including telecommunications, banking and insurance, hospitals, chemical and pharmaceutical factories and computer related industry. Some producers of mitigation devices and engineering groups were also contacted. The results from these surveys [2], [3] show that there are several possible selection criteria used within the industry:

- demand for a minimum availability of the voltage that has to be reached (e.g., six “nines”), regardless of profitability;
- appliances are divided in groups, and standard solutions for each group are provided. This can be economically beneficial, especially when the same device is in use in large numbers, and allows companies to shorten repair times when an in-stock replacement is available, improving the overall availability of the installation;
- companies tend to be loyal to one brand because of the reduction in operator faults;
- the companies surveyed relied on traditional, conservative choices for their mitigation methods (no DVR, STATCOM, etc.);
- mitigation devices for computer protection were, in many cases, placed in a redundant configuration $(N-1)$, without any economic calculations;
- mitigation devices for computer protection are often over-dimensioned, causing a low load and, thus, lower efficiency;
- large installations cannot be fully protected against voltage dips and interruptions. The main objective in this case is to limit damage to the equipment and limit the process interruption duration and its consequences.

Currently, the selection of mitigation methods is mainly based on rule of thumb, and no economic optimization is used. The surveys also pointed out that companies have difficulties comparing different mitigation methods, and selecting the optimum solution for their specific situation. Therefore we can conclude that there is a need for a methodology that returns the most economic mitigation solution for an installation susceptible to voltage interruptions and dips.

III. CASE STUDY: DESCRIPTION OF THE CASE

A. Introduction

A new evaluation method is developed enabling customers sensitive to voltage dips and interruptions to select the most appropriate mitigation method. In the following, an example of the usage of this method is presented. This example is intended to guide customers through the selection process.

B. Installation

A typical installation considered to need protection against the consequences of voltage dips and interruptions is an ICT center within a large company. These installations have are extremely susceptible to voltage dips and interruptions. For information technology industry the voltage tolerance can be described by the ITIC characteristics.[1] Furthermore, the interruption cost is experienced as being very high. The combination of both factors makes the perceived power quality costs relatively high. The rated power of these installations is typically between 40 and 400 kVA.

The case considered here is such a center, with a rated power demand of 250 kVA. The company is connected to the public grid on an open ring structure (Fig. 2). This situation is a typical medium voltage connection in a medium voltage grid such as found in Western Europe. The voltage level at the connection point is 15 kV. The center has to be online 24/7, except for the planned maintenance once a year (during a company-wide holiday). The projected lifetime is 15 years. Company policy demands a capitalization rate of 10%.

The normal procedure for a customer or company is to contact engineering companies who can propose some alternatives and among this limited range of available protection method for the customer, an optimal protection method has to be chosen. Often these offers differ significantly, but it is difficult to assess which method will provide the optimal cost-efficient mitigation in the specific case for the customer. This is where this method provides itself useful. It also provides means to compare the different options of a quotation (different possibilities of battery backup time with standard static UPS systems). The method described starts from the available quotations and uses them as input for the decision taking process.

C. Grid Connection

1) Voltage Interruptions: The connection to the public grid has an important influence on the number of process interruptions that an installation endures, since it determines the amount of voltage interruptions and their duration. Also the number of voltage dips depends on the connection. The reliability data at the connection point to the public grid can be retrieved from literature (e.g., [9]), from measurements or from contacts with the distribution grid operator. The reliability indices used here are the average number of interruptions per year that a customer experiences λ ([number/yr]), or its reciprocal, the mean time between failure (MTBF),[2] and the average interruption duration or $MTTR$ (mean time to repair, [min]). The reliability indices of a 15 kV connection in a grid such as found in Western Europe are summarized in Table I, depending on the grid connection, being directly at a HV/MV substation, or in an open-ring structure (Fig. 2).

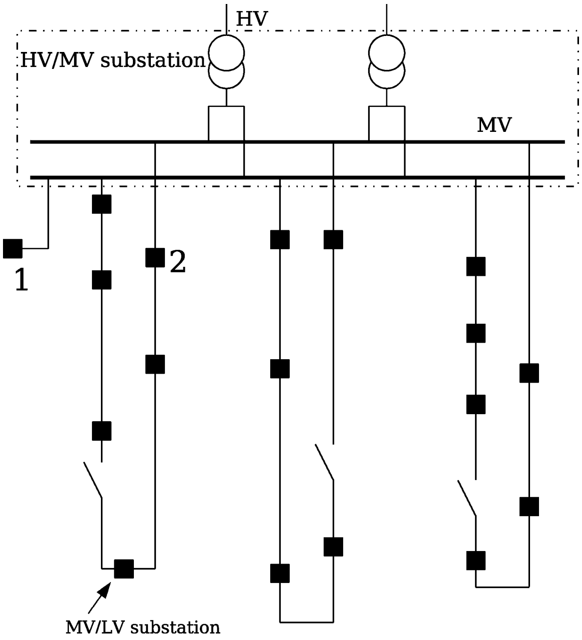

Fig. 2. Simplified scheme of a typical MV distribution grid (protection devices are not shown).

2) Voltage Dips: A large part of the process interruptions with sensitive equipment, is caused by voltage dips originating from faults on nearby branches. Estimated values of the yearly number of voltage dips can be obtained in the same way as the outage data. The average number of voltage dips expected annually at a 15 kV connection is summarized in Table I. In general, the number of voltage dips is situation dependent, but not directly linked to the number of voltage interruptions or the interruption duration. In other words, a good grid connection concerning voltage dips does not necessarily include a good grid connection for voltage interruptions.

3) Used Values: The considered values for grid reliability data at the connection point with the distribution grid that are used in the case are $\lambda = 1/\mathrm{yr}$, $MTTR = 100$ min and $\#dips = 16/\mathrm{yr}$. The influence of each of these parameters is also investigated. These values could represent a siting connected to an open ring medium voltage network with mediocre reliability conditions (Table I). Off course, these values should be obtained from measurements or from the local distribution grid operator for each independent problem assessment.

D. On-Site Reliability

1) Voltage Interruptions Caused by On-Site Events: In most cases, the sensitive equipment is not directly coupled to the utility grid, but is supplied, together with other loads, through a grid maintained by the customer. This local grid is in most

---

[1] The ITIC curve describes the voltage tolerance that typically can be tolerated by most information technology equipment [8].

[2] $MTBF \approx 8760/\lambda$ [h] when $MTBF \gg MTTR$.

TABLE I
RELIABILITY INDICES AT THE CONNECTION POINT IN A MEDIUM-VOLTAGE GRID [2]

	Case	λ [#/yr]	$MTTR$ [min]
①	Connection at HV/MV substation	0.1	60
②	Open ring connection, good conditions	0.4	60
②	Open ring connection, medium conditions	0.9	80
②	Open ring connection, bad conditions	1.8	100

Case	$\#dips$ [#/yr]
good conditions	5
medium conditions	14.8
bad conditions	30

cases radial and its influence can be calculated when the necessary reliability data is available. The techniques used are simple reliability calculations (e.g., stochastic reliability or Markov-Chain theory [10]), assuming exponential distributions. Using the Markov-Chain theory, the reliability indices for the series connection (λ_s and $MTTR_s$) and parallel connection (λ_p and $MTTR_p$) of two components (index 1 and 2) can be calculated as

$$\lambda_s = \frac{\mu_1 \cdot \mu_2 \cdot (\lambda_1 + \lambda_2)}{(\lambda_1 + \mu_1) \cdot (\lambda_2 + \mu_2)} = \frac{1}{MTBF_s} \tag{2a}$$

$$\mu_s = \frac{\mu_1 \cdot \mu_2 \cdot (\lambda_1 + \lambda_2)}{(\lambda_1 + \mu_1) \cdot (\lambda_2 + \mu_2) - \mu_1 \cdot \mu_2} = \frac{1}{MTTR_s} \tag{2b}$$

$$\lambda_p = \frac{\lambda_1 \cdot \lambda_2 \cdot (\mu_1 + \mu_2)}{(\lambda_1 + \mu_1) \cdot (\lambda_2 + \mu_2)} = \frac{1}{MTBF_p} \tag{2c}$$

$$\mu_p = \mu_1 + \mu_2 = \frac{1}{MTTR_p} \tag{2d}$$

where μ is the repair rate (i.e., the inverse of the $MTTR$). Using these four simple equations, the reliability at the terminals of the sensitive installation can be determined. The required reliability data of the grid components (such as transformers, switchgear,...) is provided by the manufacturer or can be found in the literature (e.g., [11]).

Using the available grid reliability data with the reliability data of the components in the onsite grid, the number and average duration of voltage interruptions at the terminals of the sensitive equipment can be found using Markov–Chain theory (2).

The local grid which is studied in this case is schematically represented by Fig. 3. In Table II the reliability data of the different parts of the specific network used are given (based on [11] and [12]).

2) Voltage Dips by On-Site Events: Short circuits on other branches, not feeding the sensitive load, within the company grid cause a voltage dips at the terminals of the sensitive load. The dip duration depends on the fault clearing time. This is less than 20 ms for most faults on the 230/400 V level (European voltage standards), and between 40 and 100 ms for faults on the medium voltage level. The depth of the dip depends on the relative size of the impedances of the source and the fault carrying branch. It can be assumed that the dip depth for faults on the medium voltage level is relatively high (around 50%). Another source of voltage dips is the startup current of large loads, especially grid coupled induction motors. Their influence is highly site dependent, but can be accounted for if the number of startups per year of the load is known. In this case the contribution of these events is negligible.

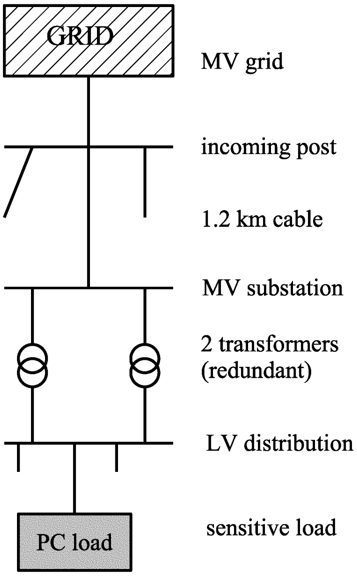

Fig. 3. Implemented onsite grid.

TABLE II
RELIABILITY DATA OF THE CONSIDERED GRID (BASED ON [11] AND [12])

	$MTBF$ [h]	$MTTR$ [min]
Incoming bus	45156	626.4
1.2 km cable	218563	3787.2
MV substation	45156	626.4
single transformer	398181	480
LV distribution	68640	76.8

E. Total Number of Process Interruptions

Not every voltage dip leads to a process interruption as only those outside the voltage tolerance characteristic cause damage. Therefore, the voltage dip distribution is also an important parameter. However, for an industrial customer, it is not easy to obtain this distribution through measurement, since a large amount of dips occurred is required to derive this, resulting in long measurement times or a large number of measurement points. Therefore, this data can be obtained from the literature [3] or again from contact with the distribution grid operator [13]. Fig. 4 shows an example of a cumulative voltage dip distribution, used for the calculations in this paper. The data are obtained from measurement in 17 substations, over a combined period of almost 30 years, resulting in the measurement of 461 voltage dips. Only voltage variations with a remaining voltage less then 90% of nominal voltage are considered.

The voltage tolerance characteristic used is the ITIC-curve [8], as it is applicable to most IT equipment.

When combining the voltage dip distribution of Fig. 4 with the voltage tolerance according to ITIC, only 31.3% of voltage dips coming from the grid, cause a process interruption (see also Fig. 5). The faults on the local grid are only harmful if they originate from the medium voltage level. It can be assumed that

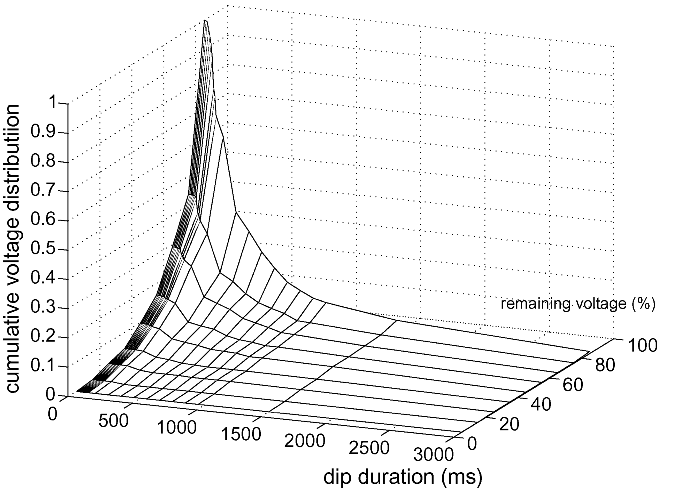

Fig. 4. Average cumulative voltage dip distribution of a medium voltage substation in a meshed grid [3].

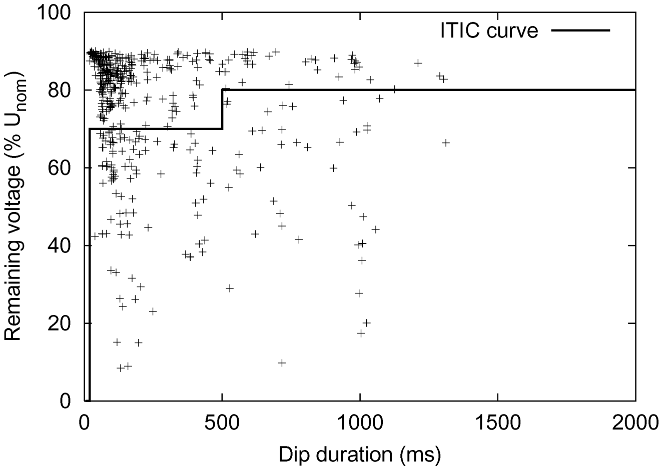

Fig. 5. Scatter plot of the measured dips and the ITIC characteristic. Only 31.3% of the dips is located outside this characteristic.

all such dips are harmful for a load with a voltage characteristic as given by ITIC. These onsite voltage dips can be calculated with the reliability data of the grid, and add about 20% to the number of harmful voltage dips.

F. Number of Process Interruptions Without Mitigation

Using the data and the methods as described in the previous paragraphs, the number of interruptions that the sensitive equipment endures when no mitigation method is used, can be calculated. For the given case, this results in 7 process interruptions per year. Of these, 1.20 interruptions are caused by voltage interruptions, with an average repair time of 3.95 h. The others are caused by voltage dips.

IV. CASE STUDY: MITIGATION COST

The cost of mitigation methods can differ considerably depending on the type of mitigation method. The cost consist of a fixed part and the operating costs.

TABLE III
INVESTMENT COST OF DIFFERENT MITIGATION DEVICES. BASED ON QUOTATIONS FROM ENGINEERING COMPANIES AND CONTACT WITH MANUFACTURERS (SOURCE: PERSONAL INQUIRIES)

	device	purchase cost (€)
①	UPS, 15 min	45,609
②	UPS, 30 min	59,150
③	UPS, 90 min	112,650
④	UPS, 180 min	173,610
⑤	2 × UPS, 15 min	91,218
⑥	Flywheel UPS, 17 s	100,720
⑦	DVR-1	45,000
⑧	DVR-2	22,000
⑨	DVR-3	51,000

A. Proposed Mitigation Devices

The typical selection of mitigation methods starts with a number of quotations, comprising different mitigation principles. These give the customer access to the following data for each mitigation device:

- apparent power;
- efficiency at different loads;
- autonomy (if applicable);
- lifetime expectancy (including, for example, batteries);
- purchase price;
- operating costs;
- installation costs;
- $MTBF$ and $MTTR$ of the mitigation system;
- contractual maintenance costs;
- mitigation capability.

The following mitigation devices are proposed by engineering companies as protection for the load:

1) 300 kVA static UPS, autonomy 15 min;
2) 300 kVA static UPS, autonomy 30 min;
3) 300 kVA static UPS, autonomy 90 min;
4) 300 kVA static UPS, autonomy 180 min;
5) 2 × 300 kVA static UPS, $N-1$ redundant, autonomy 15 min (each);
6) 250 kVA flywheel UPS, autonomy 17.2 s;
7) 215 kVA DVR-1;
8) 250 kVA DVR-2;
9) 346 kVA DVR-3.

1) Fixed Costs: The fixed costs [C_0 in (1)] mainly consist of the mitigation device cost and the cost to install it including labor hours, footprint of the device, time and so forth. The investment costs for the used mitigation methods are given in Table III.

2) Operating Costs: The operating or variable costs are those which allow the mitigation device to work. These operating costs consist of heating losses, maintenance and additional costs such as replacement of batteries at the end of their life, air conditioning to cool the battery room,... Results of the surveys [3] show that in most cases companies outsource maintenance for which the annual contractual costs are agreed in advance. In principle, the operating costs may differ from year to year.

B. Influence of Mitigation Devices

Introducing mitigation devices reduces the number of voltage dips and interruptions at the terminals of the sensitive device it protects, therefore diminishing the number of process interruptions. It is this reduction in process interruptions that determines the actual economic value of the mitigation method, and not, as is it often misconceived, the number of remaining process interruptions.

The influence of the mitigation device depends on the type used. In case of a UPS system (proposed mitigation methods 1–5), the sensitive device is interrupted in case there is an event (interruption or dip outside the voltage tolerance characteristic) during the unavailability of the UPS (UPS in bypass) or when the interruption duration exceeds the autonomy of the UPS, during the availability of the UPS (4). The number of voltage interruptions, exceeding the autonomy can be calculated when assuming on exponential distribution of the interruption duration

$$p(t > t_{aut}) = e^{-\frac{t_{aut}}{MTTR}\cdot\frac{P_r}{P}} \tag{3}$$

where

$$\begin{cases} t_{aut} & \text{autonomy with rated load;} \\ MTTR & \text{Mean Time To Repair;} \\ P_r & \text{rated power;} \\ P & \text{consumed power.} \end{cases}$$

$$\begin{aligned} \#PI_{with} = \#PI_{without} \cdot \frac{MTTR_{UPS}}{MTTR_{UPS}+MTBF_{UPS}} \\ +p(t>t_{aut}) \cdot \frac{MTBF_{UPS}}{MTTR_{UPS}+MTBF_{UPS}} \end{aligned} \tag{4}$$

where $\#PI_{without}$ stands for the number of process interruptions without the mitigation device.

Method 5 (two UPSs placed in $N-1$ redundancy) is not able to protect the sensitive device if:

- both the UPSs are unavailable and the grid is unavailable:
- when one of the UPSs is unavailable and the interruption is longer than the autonomy of the other UPS;
- if the grid is unavailable for a period exceeding the autonomy of both UPSs combined.

Mitigation methods 7–9 offer no protection against voltage interruptions, they only extend the voltage tolerance characteristic and thereby protect against voltage dips. The number of process interruptions after mitigation is equal to the number of voltage interruptions added to the number of voltage dips that are outside the extended voltage tolerance characteristic. Namely the number of dips without mitigation multiplied by the percentage of dips outside the voltage tolerance characteristic. For devices 7, 8 and 9 (DVR-1, DVR-2, and DVR-3), the relative amount of voltage dips outside the extended voltage tolerance characteristic is respectively 8.3%, 5.7% and 6.3%. These numbers are obtained combining the voltage dip distribution as displayed in Fig. 4 and Fig. 6, which shows the extension of the protected area by these devices, based on product data available from manufacturers. DVR-1 extra protects the load for events with a duration less than 200 ms and those with a remaining voltage above 50% (areas A, B and C). DVR-2 gives additional protection for voltage dips with a remaining voltage above 50% (area A). Device DVR-3 reduces the impact of voltage dips for areas A, B and D, meaning dips with a remaining voltage of 39% for 500 ms or 43% for dips that last longer. Note: a mitigation device does not need to keep the voltage at the terminals constant at the rated voltage, it suffices to keep the voltage within the limits which the device can tolerate.

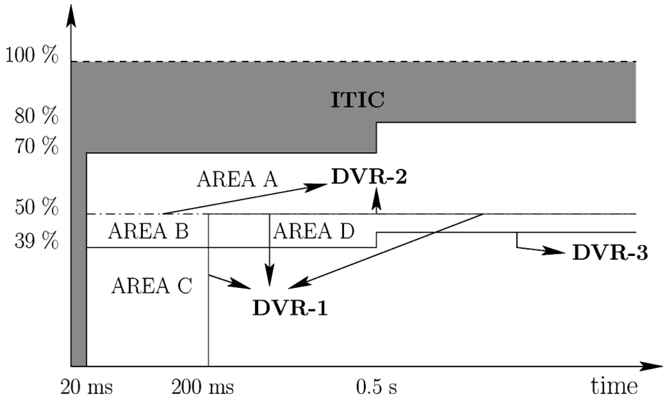

Fig. 6. Alteration of the voltage dip susceptibility by installing DVR-1, DVR-2, and DVR-3. The shade zone depicts the zone defined by ITIC.

TABLE IV
REDUCTION OF THE NUMBER OF PROCESS INTERRUPTIONS AFTER MITIGATION

method	without mitigation $\#/yr$	after mitigation $\#/yr$	reduction %	improvement $\#/yr$
1	7.0096	1.1125	84.1287	5.8971
2	7.0096	1.0279	85.3358	5.9817
3	7.0096	0.7491	89.3132	6.2605
4	7.0096	0.4661	93.3511	6.5435
5	7.0096	0.8774	87.4836	6.1322
6	7.0096	1.2025	82.8451	5.8071
7	7.0096	1.9120	72.7231	5.0976
8	7.0096	2.3280	66.7884	4.6816
9	7.0096	2.0080	71.3536	5.0016

C. Total Number of Faults After Mitigation

The combination of the result of mitigating is a reduction in number of process interruptions. For the nine methods proposed this reduction is given in Table IV. It can be noted that the installation of the two UPSs in $N-1$ redundancy in this case does not lead to the best availability. The reason being the rather limited autonomy (15 minutes per UPS) in comparison to the high average interruption duration (3.9 hours) and the high reliability of a single UPS.

V. CASE STUDY: AN ALTERNATIVE SELECTION METHOD

A. Techno-Economic Optimization

The goal of mitigation methods is the reduction of process interruptions, making the interruption costs lower. Of course, these protection methods come at a price. A techno-economic optimum is reached when the total cost of power quality (remaining process interruptions + mitigation) is minimal

$$\texttt{Min}\{C_{Total} = C_{mitigation} + C_{interruption}\}. \tag{5}$$

This can be reformulated as maximizing the return of the reduction in interruptions reduced with the additional cost of mitigating [14]

$$\texttt{Max}\{return = \#PI \cdot C_{one\ interruption} - C_{mitigation}\} \tag{6}$$

where $\#PI$ is the number of process interruptions.

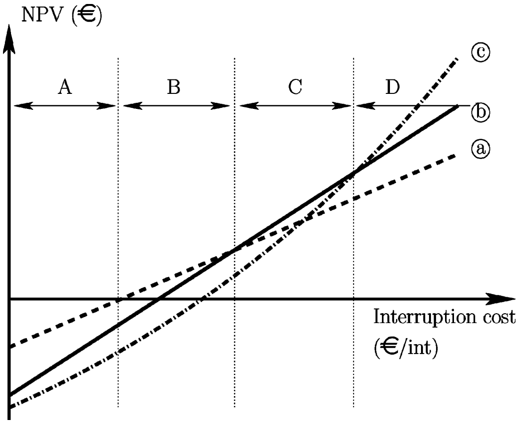

Fig. 7. Calculation of the NPV with variable interruption costs and constant grid reliability leading to intervals of interruption cost, where one optimal solution exists.

TABLE V
INTERRUPTION COST INTERVALS FOR THE CASE STUDY

Optimal investment		Interruption cost ($€/int.$)		
No investment		0	→	1,190
Investment 8:	DVR-2	1,190	→	10,340
Investment 7:	DVR-1	10,340	→	18,210
Investment 6:	Flywheel UPS	18,210	→	26,320
Investment 1:	Static UPS, 15 min	26,320	→	38,260
Investment 2:	Static UPS, 30 min	38,260	→	62,250
Investment 3:	Static UPS, 90 min	62,250	→	70,460
Investment 4:	Static UPS, 180 min	70,460	→	∞

B. *Intervals of Optimal Mitigation Method*

When (6) is applied for each mitigation method with varying process interruption costs, using the NPV method (1), the interruption cost is divided in intervals where one solution is optimal for the given grid reliability. A graphic representation of how these results can be compared is depicted in Fig. 7 where a typical graphical outcome for a situation with three proposed mitigation methods is given. The device with the highest NPV is the most economical. This means that in area B, device ⓐ is the most profitable to install, in area C, device ⓑ has a higher return and in zone D, the device ⓒ has the highest return on investment. In area A, the most profitable solution is to install no mitigation equipment and to live with the occurring process interruptions.

These ranges in interruption cost can be used in the decision making process because rough estimates of the interruption costs are available. The method gives the interruption cost as a result, not as a variable. The intervals for the given application and grid conditions are given in Table V.

It should be noted that the flywheel UPS has a higher purchase cost than the static. However it is more economic at low interruption costs. This is due to the low maintenance costs, the high availability and efficiency, small footprint but especially the longer life expectancy of the energy storage (flywheel compared to batteries). It is also interesting to note that this 250 kVA installation can be economically protected against voltage dips and interruptions from 1 190 euro/int. This is a reasonably low interruption cost for such an installation.

C. *Usefulness of the Method*

The proposed alternative selection method orders the mitigation equipment into ranges where they are most profitable. The method gives the interruption cost as a result, not as a variable, and this rephrases the investment question. If the interruption costs are known, the method enables to select the correct mitigation device for a specific situation, and if the interruption costs are only vaguely known, a well-considered decision can be made. When the process interruption costs are unknown, the method can be used in terms of willingness to pay (WTP). The results of this method are easy to interpret in this sense. For instance: method 6, the flywheel UPS is useful if the average interruption cost is at least euro 18 210 and not more than euro 26 320, since a static UPS with 15 min autonomy becomes more profitable, and thus optimal starting from that value. In other words, it is only profitable to install a static UPS with 15 min of backup time if the customers considers an average power system outage to cost over euro 26 320. The problem statement is shifted from "How much do the interruptions cost?" to "How much am I willing to pay, in order to avoid process interruptions?".

The rephrasing is especially important when the decision taking process has to be done by nonspecialists of power quality related issues or even nonengineers which is often the case in small to medium sized companies.

As could be expected, the mitigation method optimal for the highest interruption costs (method 4) is the device with the lowest number of remaining process interruptions after mitigations (see also Table IV). Note also that for the configuration examined, under the proposed conditions, the redundant configuration is in with no interruption cost optimal. This is probably due to the fact that we propose that the customer takes its installation off-line each year during company-wide holiday leave for maintenance.

VI. CASE STUDY: SENSITIVITY TO GRID RELIABILITY

Since the grid indices are only roughly known, it is interesting to investigate the influence of these values in the selection procedure. Fig. 8 (and Table V) shows the influence of λ_{grid}, $MTTR_{grid}$ and $\#dips_{grid}$, with the other variables at their original value ($\lambda_{grid} = 1/\mathrm{yr}$, $MTTR_{grid} = 100$ min and $\#dips_{grid} = 16/\mathrm{yr}$). The thick horizontal line represents the value of the example case and therefore represents the same intersection in the three subgraphs. Sensitivity to changes in grid reliability data can be seen as the alteration of the interval of optimal selection method when moving away from the examined case.

The encircled numbers represent which device is optimal in which area. From Fig. 8, it can be seen that the sensitivity to the reliability when selecting a mitigation method can be divided into two groups: mitigation methods specific for voltage dip mitigation (devices 7 and 8) and mitigation methods suitable to mitigate dips and interruptions (devices 1, 2, 3, 4 and 6). As could be expected, the first group of mitigation devices is not sensitive to variations in the number of interruptions [Fig. 8(a)] or the $MTTR$ [Fig. 8(b)], while the second group is virtually insensitive to changes in the number of voltage dips [Fig. 8(c)].

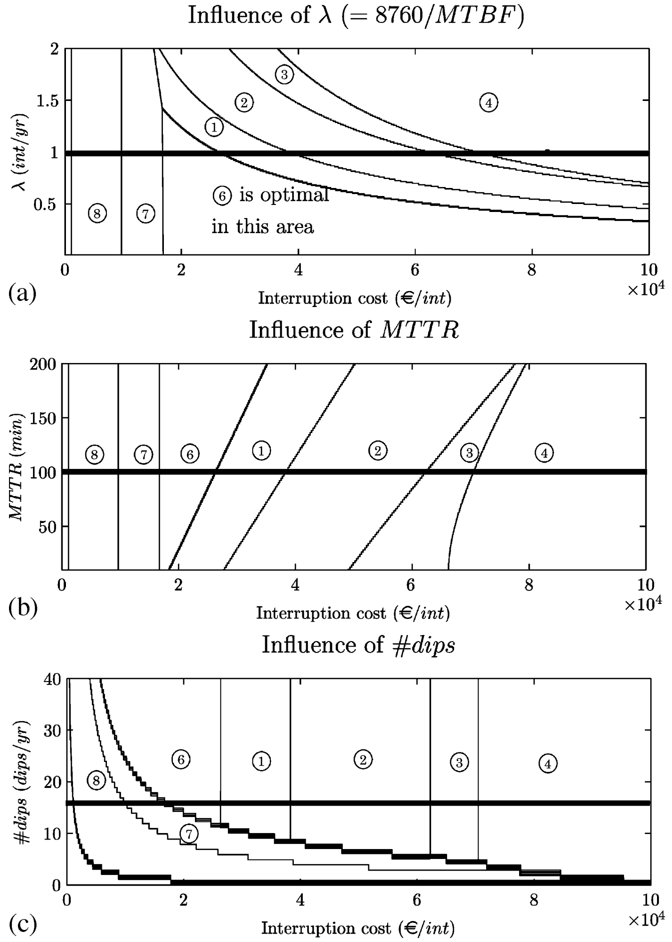

Fig. 8. Sensitivity to the different reliability indexes: (a) the number of interruptions per year λ, (b) the mean time between failure $MTTR$, and (c) the yearly number of voltage dips $\#dips$.

Variations of $MTTR$ have a small impact on the selection of the most optimal protection against dips and interruptions.

Variations of $MTBF$ [Fig. 8(a)] and $\#dips$ [Fig. 8(c)] have a noticeable influence on the interruption cost interval, but this influence is considered small enough to maintain the results of Table V for this specific case. When this assumption does not satisfy the customer, a more detailed analysis should be performed.

VII. CONCLUSIONS

This paper presented a method allowing a quantitative comparison between different mitigation methods. In all cases, it is crucial to make a clear distinction between voltage dips and interruptions and process interruptions caused by voltage dips and interruptions. The latter being those events causing the real economic damage by influencing the manufacturing process, the data stream or other processes.

If the interruption costs are known, the method enables the selection of a correct mitigation device for a specific situation, and even if the interruption costs are only vaguely known, a well-considered decision can be made. When the process interruption costs are unknown, the method can be used in terms of willingness to pay (WTP).

The problem statement is shifted from "How much do the interruptions cost?" to "How much am I willing to pay, in order to avoid process interruptions?"

The difficult process of selecting an appropriate mitigation method is simplified to a method that is easy to interpret, using only data available to the customer. This method also facilitates the comparison of totally different mitigation methods, for both specialists and nonspecialists.

REFERENCES

[1] PRIMEN, The Cost of Power Disturbances to Industrial & Digital Economy Companies CEIDS, Ed.. Palo Alto, CA, EPRI, 2001.

[2] D. Van Hertem, M. Didden, J. Driesen, and R. Belmans, "Optimal mitigation of voltage dips and interruptions," in *Proc. IEEE Young Researchers Symp. Electrical Power Engineering*, Delft, The Netherlands, Mar. 2004.

[3] D. Van Hertem, "Techno-economische optimalisatie van maatregelen tegen spanningsdips en-onderbrekingen," (in Dutch) M.Sc. thesis, Katholieke Univ. Leuven, Leuven, Belgium, Jun. 2003.

[4] M. Didden, R. Belmans, and W. D'Haeseleer, "Cost-benefit analysis of voltage sag mitigation methods in fiber extrusion plants," *Eur. Trans. Electrical Power (ETEP)* vol. 13, no. 2, pp. 73–77, Mar./Apr. 2003 [Online]. Available: http://www.esat.kuleuven.be/electa/publications/fulltexts/pub_1038.pdf.

[5] R. Brealey and S. Myers, *Principles of Corporate Finance*, 6th ed. New York: McGraw-Hill, 1999, 0-0770-9565-0.

[6] H. Khatib and A. T. Johns, *Economic Evaluation of Projects in the Electricity Supply Industry*, ser. Inst. Elect. Eng. Power and Energy series, D. F. Warne, Ed. London, U.K.: Inst. Elect. Eng., 2003, 0-86341-304-8.

[7] R. E. Brown, *Electric Power Distribution Reliability*, ser. Power Engineering, H. L. Willis, A. F. Sleva, and M. Shahidehpour, Eds. New York: Marcel Dekker, 2002, 0-8247-0798-2.

[8] Information Technology Industry Council (ITI), ITI (CBEMA) Curve Appl. Note p. 3, 2000 [Online]. Available: http://www.itic.org/technical/iticurv.pdf.

[9] A. Sumper, A. Sudrià, and F. Ferrer, "International reliability analysis in distribution networks," International Conference on Renewable Energies and Power Quality 84-607-9889-5. Barcelona, Spain, Mar. 2004, paper 4.299.SUMPER, pp. 1–5.

[10] M. Bollen, *Understanding Power Quality Problems, Voltage Sags and Interruptions*. Piscataway, NJ: IEEE Press, 2000.

[11] A. Montebaur, Zuverlässigkeitsanalysen industrieller elektrizitätsversorgungsnetze unter einschluß der productionsprozesse. Aachen, Inst. Elek. Anlagen Energiewirtschaft, 1996, no. 42.

[12] H.-J. Haubrich, Zuverlässigkeitberechnung von Verteilungsnetzen, Grundlagen—Verfahren—Anwendungen. Aachen, Inst. Elek. Anlagen Energiewirtschaft, 1996, no. 36.

[13] Hydro Québec, Characteristics and target values of the voltage supplied by the Hydro-Québec medium and low voltage systems Hydro-Québec, Varennes, QC, Canada, Tech. Rep. 30012-01-02, Jun. 2001.

[14] D. Van Hertem, M. Didden, J. Driesen, and R. Belmans, "Economic evaluation of mitigation methods against voltage dips and interruptions based on stochastic reliability," Int. Conf. Renewable Energies Power Quality 84-607-9889-5. Barcelona, Spain, Mar. 2004, paper 4.277. HERTEM, pp. 1–8.

[15] A. Chowdhury and D. Koval, "Application of customer interruption cost in transmission network reliability planning," *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, pp. 1590–1596, Nov./Dec. 2001.

[16] C. Warren, R. Ammon, and G. Welch, "A survey of distribution reliability measurement practices in the U.S.," *IEEE Trans. Power Del.*, vol. 14, no. 1, pp. 250–257, Jan. 1999.

Dirk Van Hertem (S'02) received the M.Eng. degree from the K.H.K., Geel, Belgium and the M.Sc. Eng. degree from the Katholieke Universiteit Leuven (K.U. Leuven), Leuven, Belgium, in 2003, where he is currently pursuing the Ph.D. degree.

Currently, he is a Research Assistant with the Fonds Wetenschappelijk Onderzoek Vlaanderen' (F.W.O.-Vl) at K. U. Leuven, Leuven.

Mr. Van Hertem is Chairman of the IEEE student branch Leuven. In 2001, received the VIK award for his M.Sc. thesis and, in 2004, he received the KBVE R&D award for his second M.Sc. thesis. His research interests include power quality and power system control and optimization.

Marcel Didden (M'04) received the electrical engineering degree from the RWTH, Aachen, Germany, in 1998. He received the Ph.D. degree from the Katholieke Universiteit Leuven (K.U. Leuven), Leuven, Belgium, in 2003.

From 1998 to 2000, he studied the subject Demand Side Management within a workgroup of the International Energy Agency (IEA).

Dr. Didden is a member of the Electrical Power Systems and Metrology Department of Laborelec, Linkebeek, Belgium.

Johan Driesen (S'93–M'97) was born in Belgium in 1973. He received the M.Sc. and Ph.D. degrees in electrical engineering from Katholieke Universiteit Leuven (K.U. Leuven), Leuven, Belgium, in 1996 and 2000 on the finite element solution of coupled thermal-electromagnetic problems and related applications in electrical machines and drives, microsystems, and power-quality issues.

Currently, he is an Associate Professor with K.U. Leuven and teaches power electronics and drives. In 2000–2001, he was a Visiting Researcher with the Imperial College of Science, Technology and Medicine, London, U.K. In 2002, he was with the University of California, Berkeley. Currently, he conducts research on distributed generation, including renewable energy systems, power electronics and its applications (e.g., in drives and power quality).

Ronnie Belmans (S'77–M'84–SM'89–F'05) received the M.S. degree in electrical engineering, the Ph.D. degree, and the Special Doctorate degree from Katholieke Universiteit Leuven (K.U. Leuven), Leuven, Belgium, in 1979, 1984, and 1989, respectively, and the Habilitierung from the RWTH, Aachen, Germany, in 1993.

Currently, he is Full Professor with K.U. Leuven, teaching electrical energy. He is Appointed Visiting Professor with Imperial College, London, U.K. He is also President of the International Union for Electricity Applications (UIE). He was with the Laboratory for Electrical Machines of the RWTH, Aachen, Germany and was a Von Humboldt Fellow in 1988–1989. From 1989 to 1990, he was Visiting Associate Professor at McMaster University, Hamilton, ON, Canada. From 1995–1996, he was the Chair at London University, London, U.K., offered by the Anglo–Belgian Society.

Dr. Belmans is a fellow of the Institute of Electrical Engineers (U.K.) and is Chairman of the board of Elia, the Belgian transmission grid operator.