Aalto University

AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEERING
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A Novel Approach for Assessing the Impact of Voltage Sag Events on Customer Operations

Thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Technology

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The business activities of the majority of industrial and commercial customers are dependent on some critical equipments that are susceptible to voltage sag events. Malfunctioning of sensitive devices against voltage sags has a detrimental effect on the operation of the customers. Although previous studies have proposed assessment methods to calculate the financial impact of voltage sag events on these critical devices but the approach of the methodologies are limited to specific case studies with particular customer operations and cannot be applied to diverse customers.

This thesis aims to propose a novel and generic evaluation approach for estimating the financial impact of voltage sag events on customer operations. The proposed technique is based on the event tree method. Using this approach, it is possible to consider the impacts of operational failure of various sensitive equipments involved in the customer operations on the financial losses expected from voltage sag events. A methodology, based on the developed approach, is also proposed for analyzing the effectiveness and practical viability of various voltage sag mitigation solutions. A quantitative case study is conducted in the thesis to illustrate the applicability of the purposed approach. Moreover, a comparative assessment was made to find out the applicability of various mitigation options. The method can be applied by customers to select the most economical mitigation option for their operations.

KEYWORDS: Event Tree, Interruption Cost, Power Quality, Voltage Sags, Power Quality Conditioner.

PREFACE

The work in this Master's thesis was carried out at Aalto University School of Electrical Engineering as part of the SGEM project under the supervision of Professor Matti Lehtonen.

First of all, thanks should be forwarded to God, most gracious, most merciful, who guides me in every step I take. I would like to express my deepest gratitude to my supervisor Prof. Matti Lehtonen, for accepting and giving me this wonderful research project. His supervision both helped me to channel and specify the discussed ideas and at the same time provided much appreciated freedom and support to explore new ways and concepts. His endless drive for new and better results is highly appreciated. I would also like to take this opportunity to acknowledge my instructor Shahram Kazemi for all his guidance and encouragement. Several ideas in this dissertation have been benefited from his insightful discussions. I am very grateful for his endless support, positive and motivating attitude and for his kind assistance in scientific writing in my publication.

My gratitude to all my friends for their joyous company specially to my friend Waqas Ali who has been supportive and motivating for me.

Many thanks to my brother Sauood Sadiq who has been a pillar of support and comfort during this hard time. Finally, I would like to thank my whole family, who have always been by my side and provided me with unwavering support throughout my life.

Espoo, March 2011.

Muhammad Yasir

LIST OF ABBREVIATIONS

RMS	Root mean square
AC	Alternating current
DC	Direct current
IEEE	Institute of Electrical and Electronics Engineers
ITE	Information technical equipment
EPRI	Electric Power Research Institute
ASD	Adjustable speed drive
PC	Personal computer
SD	Semiconductor devices
PLC	Programmable logic controller
DPI	Dip proofing inverter
BC	Boost converter
CHD	Coil hold-in device
UPS	Uninterruptable power supply
DVR	Dynamic voltage restorer
SEMI	Semiconductor Equipment and Materials International
ITI	Information Technology Industry
CBEMA	Computer & Business Equipment Manufacturers’ Association
COD	Cost of downtime
MV	Medium voltage
HV	High voltage

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Nowadays, in the domestic market, electricity is considered as the basic right of every individual and it should be always available at all times. The electricity is taken as a product with certain characteristics which needs to be calculated, predicted, improved and assured [1]. The issues related with electric power transmission is not limited to only energy efficiency but more importantly on quality and continuity of supply or more specifically power quality. Power quality is “set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform)” [2].

Most of the power quality issues are related to the magnitude of the voltage. Ref. [1] makes a clear distinction between various phases of power quality issues related to voltage magnitude.

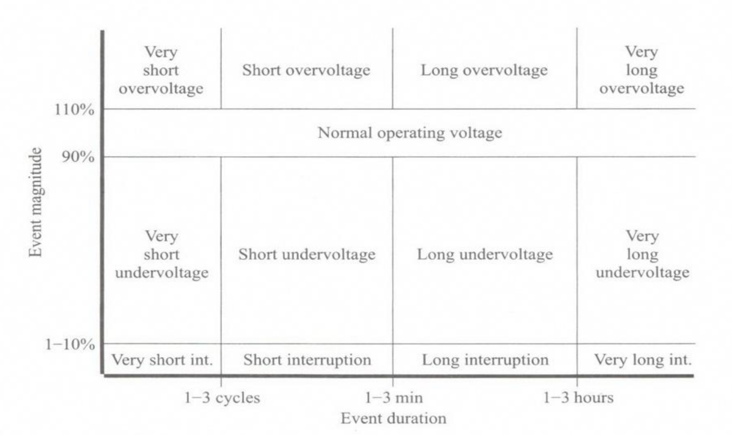


Fig. 1.1 Classification of power quality issue based on voltage magnitude [1].

Factors that are driving interest and serious concerns in power quality are increased load sensitivity, automation and increased efficiency.

Power electronic and electronic equipments have turned to be more sensitive than its equivalent equipments developed 1 or 2 decades ago [1]. This increased sensitivity of the equipments to voltage sags has highlighted the importance of quality of power, the electric utilities and customers have become much more concerned about the quality of electric power service. Modern power electronic equipment is sensitive to voltage variation and it is also the source of disturbances for other customers [1].These factors have developed together with time and with overall development of the electrical industry. This rising sensitivity of equipments has drawn attention to more awareness of short interruptions and voltage sags. For specific customers the financial losses caused by these short duration phenomena may even be greater than the cost associated with the interruptions [3]. Extensive use of automation and electronic items has made it important for the electric utilities to improve the quality of supply and service to customers.

Voltage sag can affect the majority of sensitive equipments like personal computers (PC), adjustable speed drives (ASD), programmable logic controllers (PLC), semiconductor devices (SD) and contactors. The successful running of an operation is dependent on the working of the above mentioned sensitive equipments.

1.2 SCOPE

To avoid high financial losses in automated plant operations, the need to keep the process equipment running is of extreme importance. Any disruption can lead to downtime which can directly result in loss of production, revenues and profits. From various power quality disturbances, voltage sags are most frequent [4] and result in highest financial loss because voltage sags cause frequent mal-operation of the equipment [5]. The occurrence of voltage sag events is far more than the number of power interruptions. Therefore, for specific customers, the financial losses caused by voltage sag events may even be greater than the cost associated with power interruptions. The increased sensitivity and high costs associated with such events are acting as a driving factor for increasing interest to study and to reduce the effects of voltage sags on customer operations. Since the voltage sags are critical for customers, power distribution companies should take into account the characteristic of the voltage sags experienced in their network. Moreover, effect of alternative system configurations on voltage sags should be estimated by the electric power companies along with the possibility to minimize the inconvenience originated by the voltage sags. [3]

1.3 OBJECTIVE

In this thesis, the main objective is to propose a generic assessment method which can be applicable to any customer operation and it can help in calculating the financial loss resulted due to malfunctioning of the operation due to the voltage sag events experienced by the customers connected to the power distribution networks. The major aspect here is to introduce a novel approach by which financial impact of voltage sag is calculated on different customers connected to the grid during a year. A simplified but comprehensive methodology has been introduced and developed.

Main contributions introduced by this thesis are:

- A novel approach for assessing voltage sag impact in terms of financial losses onto the customers.
- The proposed technique is based on the event tree methodology which makes it more comprehensive and adaptable for a variety of customers having different processes or operations.
- Impact factors assigned to each event tree outcome based on the contribution of sensitive devices in the operational failure of the process, presents the different failure states of the process.

- Comparative economic analysis of various mitigation options on control level, machine level and factory level.
- Feasibility of different mitigation schemes implemented on diverse levels of the process.
- A case study has been discussed to present the practical adaptability of the procedure.

Voltage sag impacts are expected to change if certain improvements are carried out on the network as well as on the customer side.

With the help of the methodology presented in this thesis, the influence of the voltage sags can be interpreted in terms of the financial losses resulted by the downtime occurred at the customer side. Accurate estimation of losses incurred by voltage sags can enable power distribution companies to make their system more redundant by making alteration in their switching schemes so that customers connected to their network can have less impact of the voltage sags. In this way, power distribution companies can make improvements in the reliability of the network and cope up with the ever increasing demands coming from the electricity authorities and the more demanding customers.

1.4 DISPOSITION

This thesis consists of six chapters. The first chapter gives a brief overview and introduction of the topic. Second chapter provides the details about voltage sags, giving thorough knowledge of characterization and origin of voltage sags. It also introduces the voltage tolerance curves for the sensitive devices that are mostly used in the customer operations. In chapter 3, various mitigation options are briefly reviewed.

The major objective of this thesis is stated in chapter 4 where a novel assessment methodology has been proposed for calculating the financial impact of voltage sag events on customer operations. The computation method is generic and can be applied for a variety of customers. Moreover, it can be used in calculating the most economical mitigation option for an operation. In chapter 5, a case study is discussed in which practicality of the proposed method has been presented. In the end, the thesis is concluded in chapter 6.

CHAPTER 2

VOLTAGE SAGS

2.1 INTRODUCTION

The most prominent and commonly occurring power quality issue is voltage sags. The main reason of this highlighted area is the negative effect which voltage sags has on the working of several types of sensitive equipments. These sensitive equipments may trip when the RMS voltage drops below 90% for longer than one or two cycles [1]. The tripping is normally caused by the over-current protection or under-voltage protection and these two protective measures work independent of each other. Voltage sag can occur due to short circuit fault located hundreds of kilometers away from the affected area. This makes it much more complicated than other power quality problems. Typical causes for generation of voltage sags are short circuit faults, switching operations, lightning strikes and starting of induction motors.

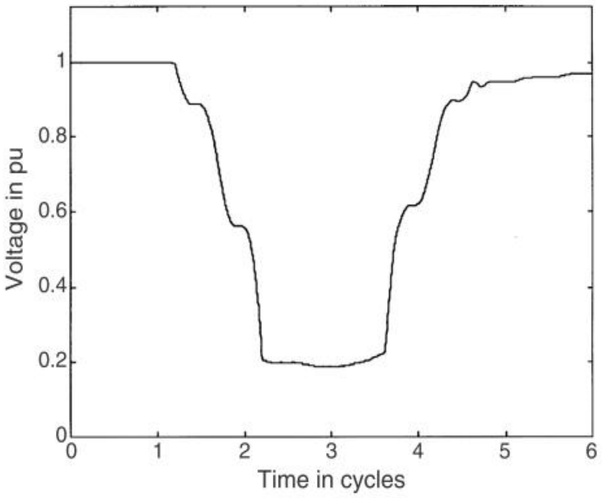


Fig. 2.1 Voltage Sag due to short circuit fault [1].

2.2 CHARACTERIZATION OF VOLTAGE SAGS

Voltage sags are mainly characterized by the following:

- Voltage sag magnitude
- Voltage sag duration
- Sag frequency (number of voltage sags experienced annually)

The definition given by the standards interpret the voltage sags in terms of magnitude and duration. Besides these considerations, there are other parameters as well:

A) Phase angle jump:

A short circuit fault in the system produces a change in the magnitude as well as in the phase angle. These phase angle jumps are more important for the power electronics converter which utilizes phase angle information for firing the converters. The main origin of phase angle jumps is the transformation of sags from high voltage levels to low voltage levels and also due to the difference in the ratio of reactance to resistance (X/R) between source and the feeder.

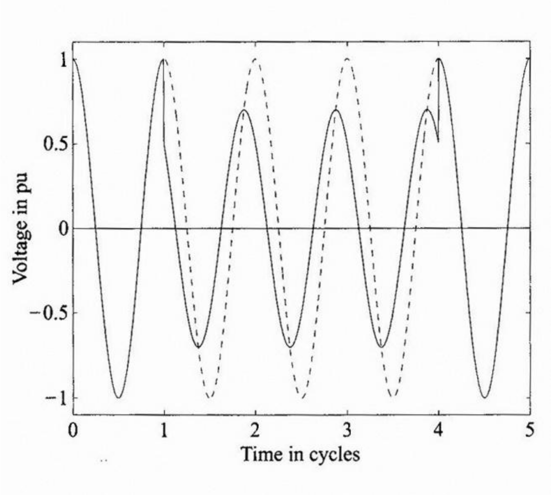


Fig. 2.2 Voltage sag of magnitude 70% with a phase shift of +45^o [1].

B) Point-on-wave characteristics:

It is the phase angle of the fundamental voltage wave where the voltage sag starts. A reference point is taken for computing point-on-wave of sag initiation. Normally the upward zero crossing of the fundamental voltage is taken as a reference.

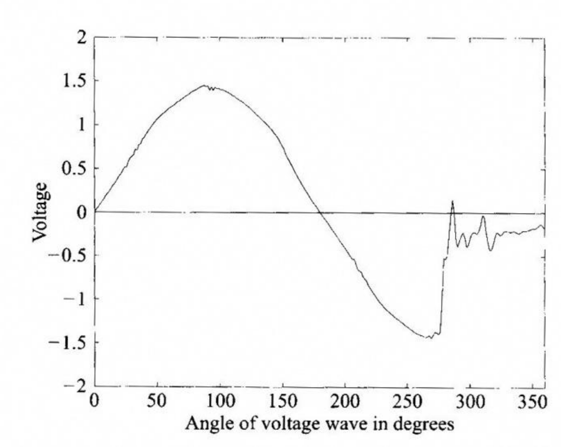


Fig. 2.3 Point of wave is in between 276^o and 280^o [1].

In the above Figure, point of sag initiation or point-on-wave of sag initiation is near to the peak voltage value.

2.3 DEFINITION

The European standard EN 50160, voltage characteristics of electricity supplied by public distribution systems describe voltage sag as “A sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage U_c, followed by a voltage recovery after a short period of time. Conventionally the duration of a voltage dip is between 10 ms and 1 minute”.

IEEE standard 1159, IEEE recommended practice for monitoring electric power quality defines a voltage sag event as “the decrease in the rms voltage between 0.1 pu and 0.9 pu for durations from 0.5 cycles to 1 minute”.

The sag magnitude is represented by many terminologies like “missing voltage” and “remaining voltage”. But it can have contrary meanings. Therefore it is quite necessary to properly define the meaning of the terms representing voltage magnitude. In this thesis, IEEE std. 1159 has been used. It states the magnitude of the voltage as the remaining voltage during the sag. For example 70 % sag in 120 V systems means that remaining voltage is 84 V. A larger value of sag magnitude corresponds to less severe sag. The terms “dip” and “sag” represents the same phenomenon and are used in this thesis alternatively.

The terms “shallow sag” and “deep sag” represent characterization of the voltage sags. “Shallow sag” means sags whose remaining voltage is high. On the contrary, “deep sag” characterizes a voltage sag with a low remaining voltage [1].

2.4 ORIGIN OF VOLTAGE SAG

There is variety of factors causing voltage dips in a power system network. Normally, the voltage sags are caused by the faults in the HV transmission and sub-transmission systems or the MV distribution itself. In case of weak power system network, sags are spread from the neighbouring MV distribution systems to a wide area.

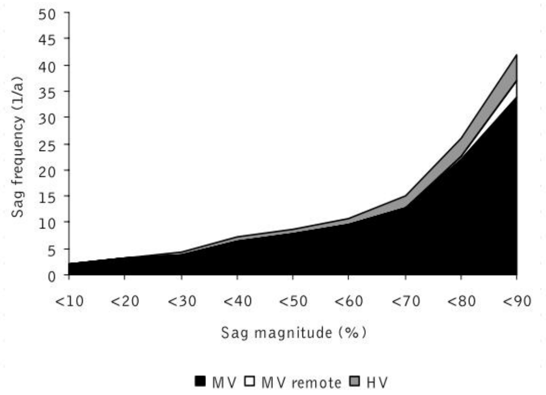


Fig. 2.4 Distribution of sag spreading on different power system levels, HV refers to the transmission and sub-transmission systems, MV is the local MV network and MV remote refers to neighboring MV distribution systems [6].

Voltage sags are primarily caused in the events in which large amount of current flows through the network impedances. These heavy currents causes voltage drop on the respective impedances, which in turn is cut off by the action of the over current protective devices.

2.4.1 Faults:

Majority of the sags are mostly caused by the power system faults. A short circuit fault is the typical fault. The type of sag greatly depends on the nature of fault. Out of majority of the sags caused by faults, most of the sags are shallow. A 3-phase short circuit near to a distribution substation can bring down the voltage of main busbar and therefore all the customers connected to that busbar will face deep sag [7].

The main reason for power system faults are:

- Weather (lightning, wind, snow)
- Wildlife (birds, squirrels)
- Equipment failure

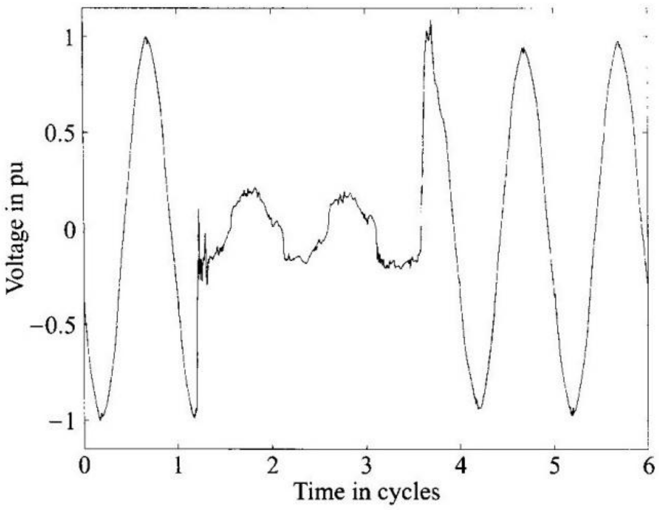


Fig. 2.5 Voltage sag due to short circuit [1].

2.4.2 RECLOSER AND CIRCUIT BREAKER

Operation of a circuit breaker or recloser causes a temporary disconnection of a specific line. Particularly in case of weak grid, this temporary fault of the line will be observed as voltage sag to the customers in the neighbouring lines of the disconnected line. The extent of the voltage sag is determined by distance from fault and supply voltage.

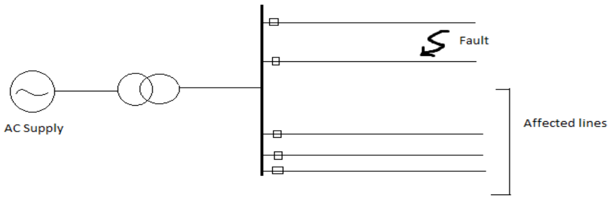


Fig. 2.6 Voltage sags in the neighbouring lines.

2.4.3 Transformer energizing:

Several transformers are connected to the MV feeders. While energizing an MV feeder, all the transformers tend to energize at the same time causing very high inrush currents. These high inrush currents cause a short duration voltage drop which is experienced by the customers in the entire area.

2.4.4 Starting of Induction Motors:

Induction motor takes a high current in starting up, which is about five to six times greater than the nominal current taken by the motor [1]. The inrush current tends to remain high until the induction motor starts running with the nominal speed. The voltage drop depends on

- Power system parameters
- Specification of the induction motor

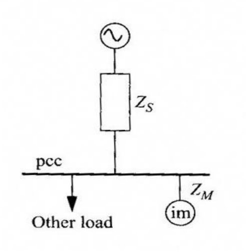


Fig. 2.7 Example of circuit having a voltage sag due to motor starting [1].

Voltage divider rule is applied for calculating the amount of voltage taken by other load from the same bus as shown in the above Figure.

$$V_{sag} = \frac{Z_M}{Z_S + Z_M}$$

2.5 EFFECT OF VOLTAGE SAGS ON SENSITIVE EQUIPMENTS

Usually successful running of customer operations depends on sensitive equipments. These electrical equipments can be categorized as:

1. Personal computers (PC)
2. Adjustable speed drives (ASD)
3. Programmable logic controllers (PLC)
4. Semiconductor devices (SD)
5. Contactors

Electrical devices operate efficiently when the RMS voltage is constant and its value is equal to the nominal value. But in the realistic world, the supply voltage is always not same and its value can change at times due to certain phenomena explained in beginning of the chapter 2. Voltage sags normally affect each phase of three phase system differently but normal approach is to present the voltage sag with the lowest of all three phase voltages and sag duration is the time until all the three phase voltages have recovered above 90% [41].

Susceptibility of customer operations against voltage sag events depends on the ride-through capabilities of its equipments against these events. In reality, the ability of every equipment to withstand voltage sag event is different and it varies from device to device from the same manufacturer. But generalized voltage limits are provided by the manufacturer, under these limits the electrical device continues to work normally. The voltage limits are presented in the form of voltage tolerance curve. Thomas Key introduced this concept of voltage tolerance curve in 1978 [8]. In this thesis, voltage tolerance curves are referred as characteristic curves.

2.6 CHARACTERISTIC CURVES OF SENSITIVE EQUIPMENTS

A characteristic curve represents the behaviour of sensitive devices to voltage sag events having different magnitude and duration. In this thesis, the “rectangular voltage-tolerance curve” is used as shown in the following Figure. Although all the equipments related to specific equipment category do not show same sensitivity against the voltage sag but all the sensitive equipments considered in this thesis exhibit, more or less, perfect rectangular characteristics [5].

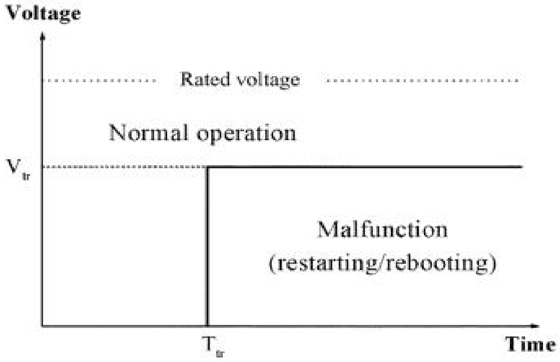


Fig. 2.8 Rectangular voltage-tolerance curve [10].

Device will malfunction if it is exposed to a voltage sag event in which the magnitude of the voltage is less than V_{tr}(threshold voltage level) and longer than the duration T_{tr} (threshold time duration value). The characteristic curves can be used to study the effect of a voltage sag events, it can help in understanding the behaviour of the device in case of voltage dips.

Various tests have been performed and published in many research articles and standards [5], [7], [9] – [10], [20], [21]. Based on published results, the author has assigned the characteristics curves for the sensitive equipments which are stated in upcoming articles:

2.6.1 PERSONAL COMPUTERS (PC)

Sensitivity of the PC to voltage sags is represented by characteristic curve provided by Information Technology Industry (ITI). It was published by Technical Committee 3 (TC3) of the Information Technology Industry Council, formally known as the Computer & Business Equipment Manufacturers' Association, (CBEMA).

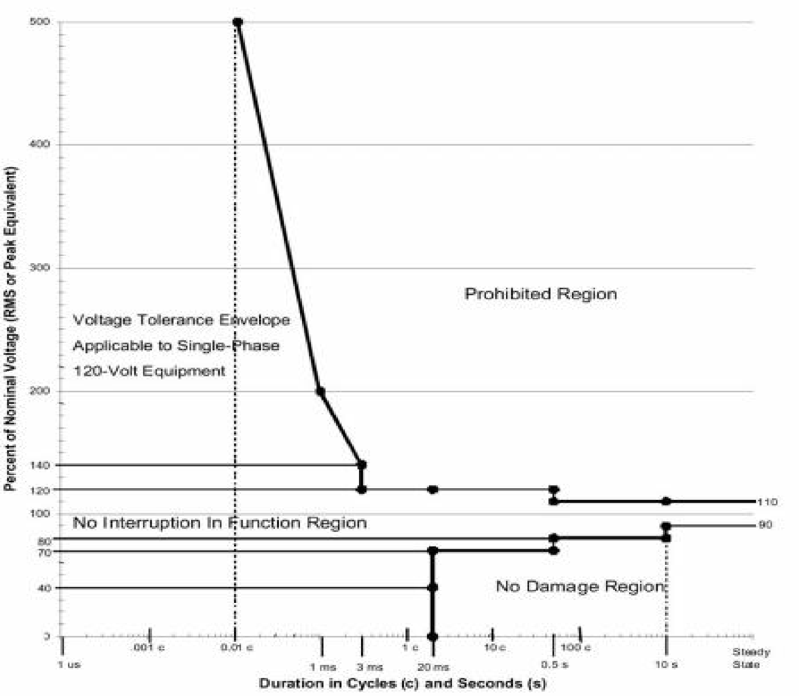


Fig. 2.9 Characteristic curve of PC (ITI curve) [21].

The ITI (CBEMA) curve describe an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE) like PC. The curve basically assumes nominal voltage to be 120 VAC RMS and it is meant for single phase ITE [IEEE 1100-1999]. Although it is mentioned in its scope that it is not intended to serve as a design specification for AC distribution systems but it is used by designers in many manufacturing companies.

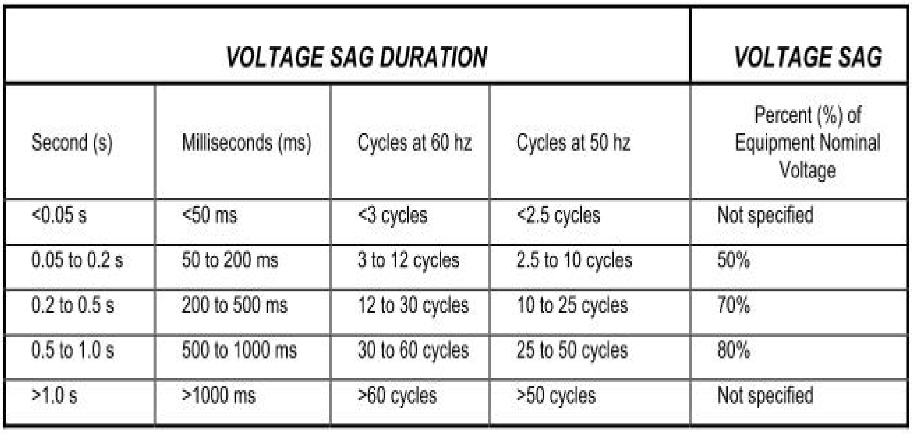
2.6.2 SEMI CONDUCTOR DEVICES (SD)

Semiconductor Equipment and Materials International (SEMI) offers international standards and recommendations for improving the voltage sag tolerance capabilities in equipment system design for semiconductor industries.

The SEMI F47-0200 standard specifies the required voltage sag ride-through for semiconductor fabrication equipment. It specifies set of minimum voltage sag immunity requirements for equipment used in the semiconductor industry. Immunity is indicated in term of voltage sag duration (cycle/ seconds) and voltage sag depth (percentage of the remaining nominal voltage) [9].

Minimum voltage sag immunity requirements are presented in the following Table and graph.

Table I



VOLTAGE SAG DURATION				VOLTAGE SAG
Second (s)	Milliseconds (ms)	Cycles at 60 hz	Cycles at 50 hz	Percent (%) of Equipment Nominal Voltage
<0.05 s	<50 ms	<3 cycles	<2.5 cycles	Not specified
0.05 to 0.2 s	50 to 200 ms	3 to 12 cycles	2.5 to 10 cycles	50%
0.2 to 0.5 s	200 to 500 ms	12 to 30 cycles	10 to 25 cycles	70%
0.5 to 1.0 s	500 to 1000 ms	30 to 60 cycles	25 to 50 cycles	80%
>1.0 s	>1000 ms	>60 cycles	>50 cycles	Not specified

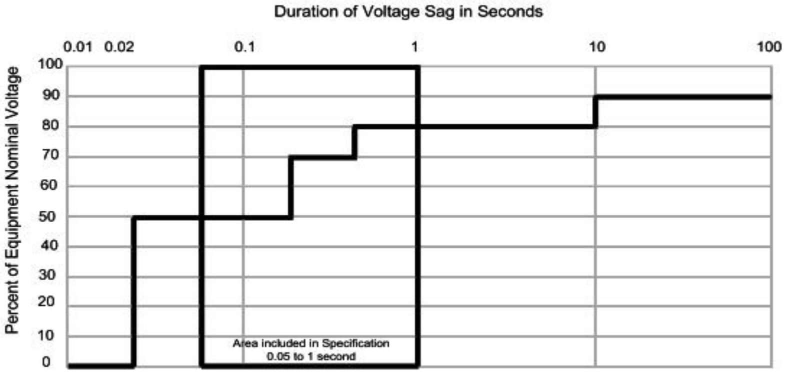


Fig. 2.10 Recommended semi conductor equipment voltage sag ride through tolerance curve [9].

2.6.3 Adjustable Speed Drive (ASD)

The main purpose of ASD is to control the speed of a synchronous or induction motor. The change in behaviour of the ASD to voltage sag conditions can have a deep effect on the industrial operations involving ASD. The ASD must be able to work smoothly in order to avoid any disturbances for the sensitive loads. It should be immune to limited number of disturbances [4].

The IEEE Standard 1346-1998 provides a methodology for the technical and economic analysis of compatibility of sensitive process equipment with an electric power system. It also contains some examples of performance of sensitive devices to voltage sag events.

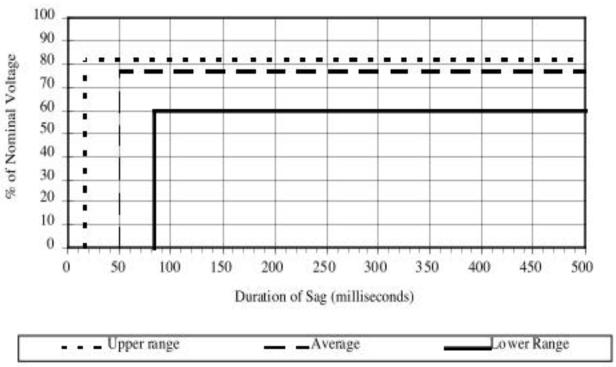


Fig. 2.11 ASD voltage sag ride through tolerance curve [20].

2.6.4 Programmable logic controllers (PLC)

The success of the modern industrial world lies within the automation of the processes. The automation of most of the elctromechanical processes in industries is done by digital microprocessor based device called PLC. Majority of the sensitive devices working in a process are given control signal by PLC. Thus the smooth running of the industrial operation is dependent on successful operation of it. Voltage dip is one of the most critical power quality problems which can have a serious effect on the operation of PLC as it is quite susceptible to the voltage value.

Voltage tolerance characteristic of PLC is based on the test result published in [5].

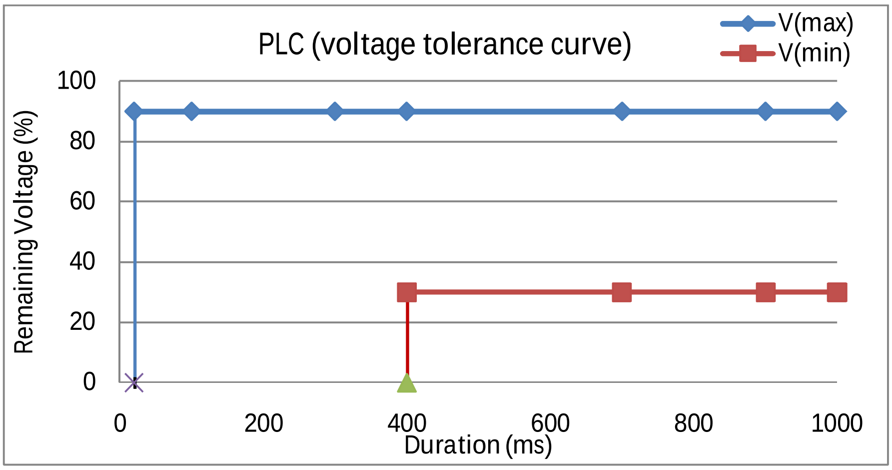


Fig. 2.12 PLC characteristic curve [5].

2.6.5 Contactors

Contactors and ac relays, here will be referred as contactors, are used for connecting loads, normally motors, to the power system [7]. It offers a robust and economical way to switch high currents in low voltage circuits. It is typically utilized for the motor starting in series with the primary circuit. Contactor can have an intense impact on the industrial operation if voltage sag causes it to drop out which in turn can shutdown the whole process. This tripping of a simple device can bring down the complicated industrial process. Therefore, special attention should be given to this conventional device while studying the impact of voltage sag on industrial operations.

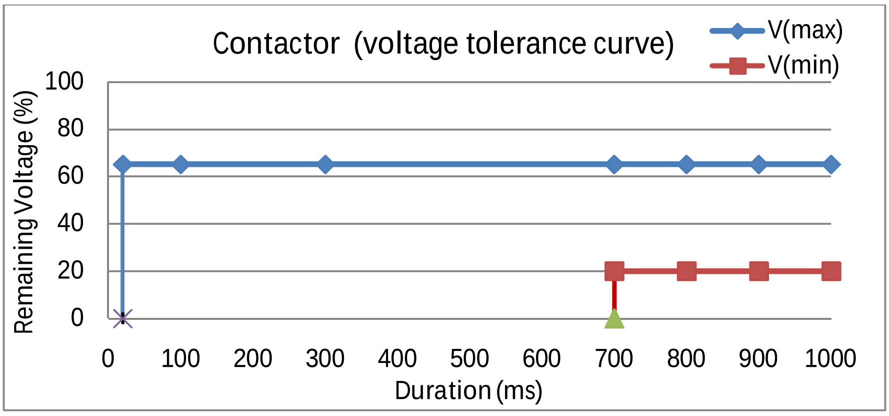


Fig. 2.13 Contactor characteristic curve [7].

CHAPTER 3

VOLTAGE SAG MITIGATION SOLUTIONS

3.1 INTRODUCTION

As power system network is not an ideal network in the real world, therefore the momentary disturbances should be expected from the utility. For the majority of the customers, the momentary disturbance in the power supply is not of utmost importance as their operations may not be effected by such events which last for a short duration. But it does affect some specific customers, as their process is terminated with such events and it costs high financial losses as their operations need to be restarted. So, there is a need for protecting the customer operations which are more vulnerable to voltage sags. One of the main momentary disturbance causes is voltage sag.

The voltage sag mitigation solutions can be applied at many levels which range from the customer facility to the utility sub-transmission feeders. Different levels are explained by the following Figure [12] as:

1) Equipment level
2) Control level
3) Overall protection of facility
4) Utility level

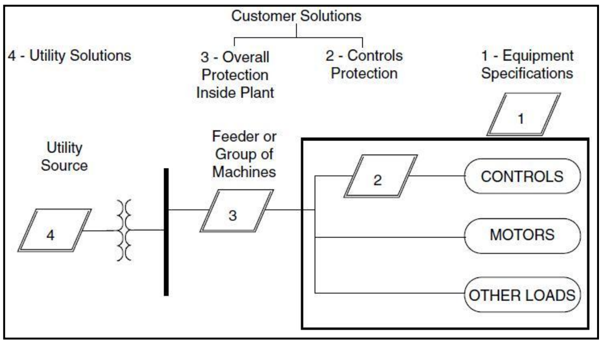


Fig.3.1 Possible levels for employing the voltage sag mitigation solutions [11].

The optimal type, number and location of voltage sag mitigation solution are determined based on the economical realization, vulnerability and importance of the customer operations. The selection of the mitigation solution depends on the load requirement in case of disruption in the power supply. In the following subsections, the general characteristics of major technologies available for implementation of voltage sag mitigation solutions for levels 1 to 3 are briefly discussed. Alternatives for level 4, utility solution, are out of the scope of this thesis.

3.2 COIL HOLD-IN DEVICES (CHD)

These devices fall into the category of equipments meant for mitigating the effect of voltage dips on individual contactors and relays.

Fig. 3.2 Voltage sag protection performance [12].

CHD can provide voltage ride through capability to about 25 percent of the nominal voltage [12]. It is installed in line with the incoming line to the contactor or relay. The specification of relay is dependent on the resistance of the coil; normally the device is sized based upon it which decreases with the increase in size of relay or contactor [15]. This device serves as a very economical resource in propping up relay and contactor loads.

3.3 BOOST CONVERTER (BC)

This device is the equipment level solution and can be utilized by connecting it with the DC bus of ASD to make it more resistant to voltage sags. ASD is mainly tripped when the DC bus voltage drops below a threshold value. The BC can be incorporated in the DC bus or it can also be installed parallel to the ASD as depicted in the Figure below [13].

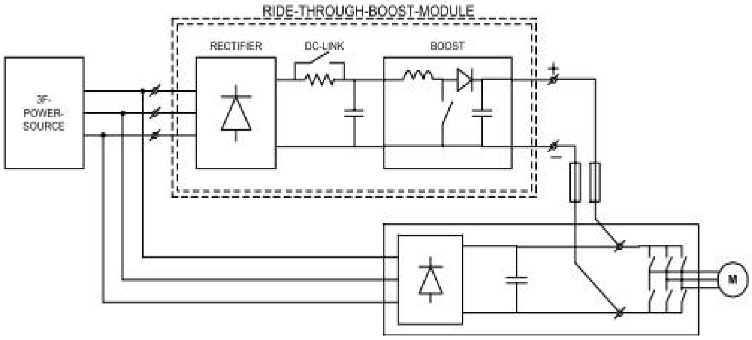


Fig. 3.3 ASD supplied with parallel boost converter [13].

It comprises of diode rectifier with DC bus and DC boost module. It is triggered only when threshold level is reached and DC bus voltage is maintained at the threshold level. To make the supply voltage steady state above the threshold value, the boost diode rectifier takes in high discontinuous current. This high inrush current can cause supply voltage to decrease further.

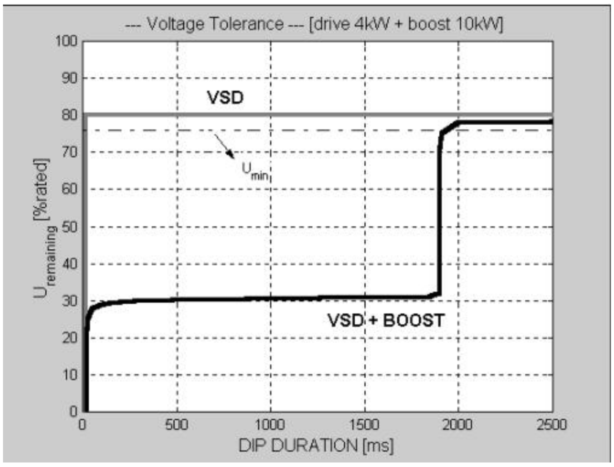


Fig. 3.4 Voltage tolerance curve of ASD having a parallel boost converter [13]

Commercially available boost converter can help ASD to withstand voltage dips with the remaining voltage up to 50% of the nominal voltage for up to 2 seconds [13]. It cannot be effective in case of an outage or deep sag as it doesn't have the capability to provide voltage to the DC bus of an ASD in case the supply voltage is below 50% of the nominal value.

3.4 UNINTERRUPTABLE POWER SUPPLY (UPS)

This device is almost the equipment level solution but it can also be used as the plant level. It is basically an electronic device that supplies electricity to the load during a supply failure from utility or in case the supply voltage falls out of its nominal value. The standard for UPS system is IEC 62040-3 [16].

UPS comprises of three types:

1) On-line UPS
2) Off-line or standby UPS
3) Line Interactive UPS

The generic UPS device consists of energy storage backup battery, an AC-DC charger and DC-AC inverter. The incoming AC power charges the batteries after rectification in to DC. Inverter converts it back into AC to feed the load.

3.4.1 On-line UPS

The on-line UPS continuously feeds the conditioned power to the load and charging of batteries are done at the same instant, therefore it must be sized properly so that it can cope up with the inrush current for the load. In case of failure of supply, the supply line is disconnected by the static bypass switch and the battery starts to feed the load automatically.

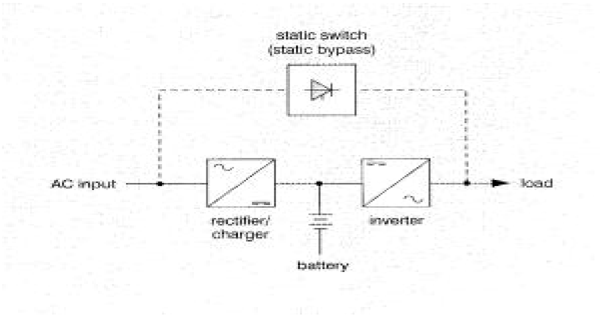


Fig. 3.7 Online UPS

The optimum design includes a ferro resonant transformer on the front end of the unit to diminish the effect of noise and voltage swell.

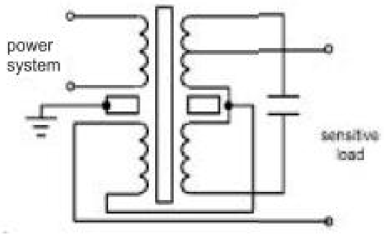


Fig. 3.8 Ferro resonant transformer.

For the safe continuous operation of the process, the transfer time from AC supply to battery should not be greater than 4ms [11].

3.4.2 OFFLINE UPS

Unlike the online UPS, the offline or standby UPS feeds the load in case of disturbance (voltage or outage). Sensitive equipments are not affected by the voltage sag if there is a high speed switching (<1 cycle) from utility power to battery. One disadvantage of offline UPS is its inability to handle voltage swells or noise. [15].

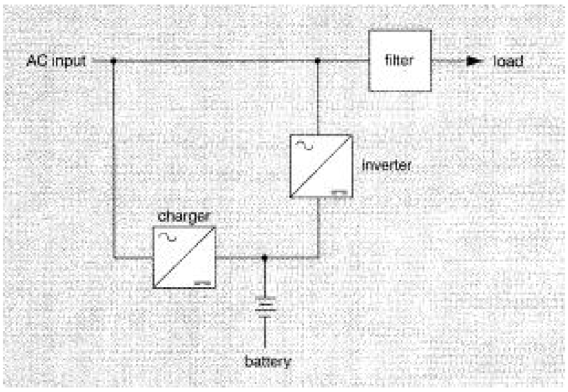


Fig. 3.9 Offline UPS

3.4.3 LINE-INTERATCIVE UPS

It falls into the category of offline UPS but the distinguishing feature of line interactive UPS is that in normal state, it tries to smooth out the incoming AC voltage with the help of a filter and a tap changing transformer. During ordinary operation, input AC supply is used to charge up the batteries. Transfer switch connects the load with the battery in case of supply failure.

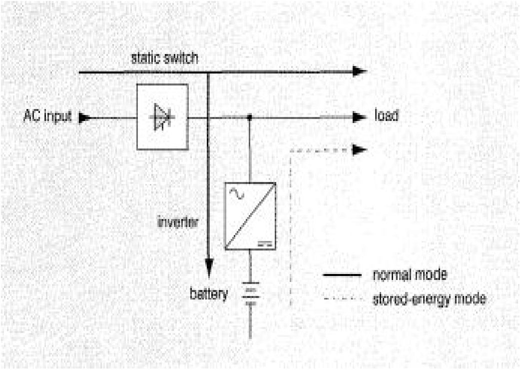


Fig. 3.10 Line interactive UPS

Due to absence of frequency regulation of line interactive UPS, it is not recommended for sensitive loads with medium to high power ratings. It is only viable for limited range of applications with low power rating [17].

3.5 DYNAMIC VOLTAGE RESTORER (DVR)

It comes into the category of static series compensator. This device can be used at the plant level. It consists of a wave synthesis device having fundamental principle based on power electronics, connected in series with the help of a set of single phase insertion transformers to the utility primary distribution circuit. The DC capacitor acts as an energy buffer, producing and absorbing power during voltage sags and voltage swells respectively [18]. In voltage sag events, it can add voltage in series with the utility voltage supply to compensate for the drop in voltage. Triggering of DVR is done within six milliseconds in the event of a voltage disturbance [15].

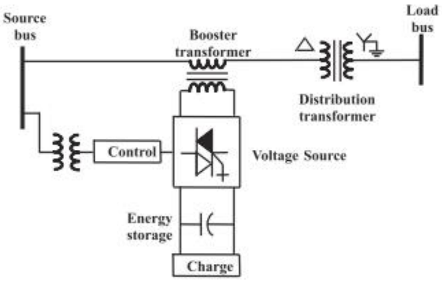


Fig. 3.11 Fundamental design of DVR.

It can provide protection only against voltage sags with remaining voltage up to 50% of the nominal voltage [15]. With the help of DVR nominal voltage is available to the load whenever a disturbance occurs upstream in the network [19].

3.6 DIP PROOFING INVERTER (DPI)

This device is the equipment level solution and belongs to the class of offline uninterruptable power supply (UPS) which operates without batteries. Due to the absence of the batteries, it doesn't require regular maintenance. The body of the DPI is quite compact and light weight as compared to UPS. [15]

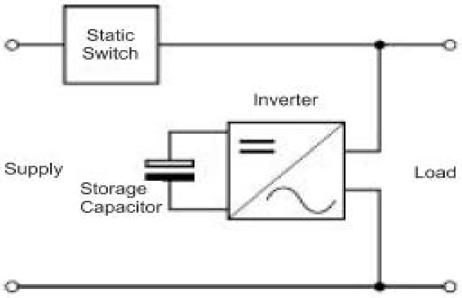


Fig. 3.5 Block diagram of DPI

In normal configuration, this device charges its DC bus capacitors by rectifying the incoming AC voltage. In the case of voltage sag below a threshold level, incoming power is disconnected from the equipment and DPI starts to feed a square wave input to the load. The time duration in which the device can feed the load is based on the real power and energy storage of the particular DPI and it can be calculated from the following formula [15]

$$time\ duration = \frac{\text{Usable stored energy (joules)}}{\text{Load power required (watts)}}$$

Fig. 3.6 Voltage tolerance curve for DPI [14].

The transfer time from supply to dip proofing status is less than 700 micro seconds [14]. The DPI can continue to supply voltage for about one to three seconds and correct voltage sag events. It can also maintain the supply voltage in case of an outage but the maximum length of duration in which it can supply voltage to the attached device is limited to three seconds [14]. The DPI output is a square wave which does not have any major compatibility issue with most of the electrical components.

CHAPTER 4

VOLTAGE SAG IMPACT-COST ASSESSMENT METHOD

4.1 LITERATURE RIVIEW

Due to the fact of increasing awareness about the power quality issues, there is a substantial increase in research in this area. Among all the power quality issues, voltage sags are important because of its detrimental effect on the customer operations. As there is a vast diversity in the customers connected to same grid, so cost of losses accompanied with the voltage sag events vary from customers to customers in the same area. The financial impact on the customers greatly depends on the nature of operation of the customers.

This highlighted topic has been addressed by number of researchers. Although a good number of papers have been published in the relevant area [22]-[27], but due to diversity of customers and complexity of operations, this area is still under study.

This section includes a brief overview of assessment methods proposed by different authors for finding the negative effect of voltage dips on the customers.

4.1.1 COST OF DOWNTIME (COD)

The generalized idea of using cost of downtime (COD) of an operation for calculating the impact of voltage dips has also been addressed in the power quality literature [20], [31]-[32].

$$CODT = DC + RC + HC \qquad (4.1)$$

Where:

CODT = Cost of downtime time.

DC = Direct cost.

RC = Restart cost.

HC = Hidden cost.

In reference [22], a methodology has been presented to calculate the post process failure cost of downtime which can be estimated by direct online cost or historical data. This proposed COD assessment procedure is specifically valid to aseptic manufacturing facility. But the main idea of the given methodology can be applied to a continuous manufacturing operation. The practicality of this estimation tool has been presented by applying the model cost of downtime on a pharmaceutical manufacturing facility.

4.1.2 STOCHASTIC ASSESSMENT METHOD

A generalized stochastic assessment of annual financial losses due to voltage dips and interruptions has been suggested by authors [23] - [24]. The methodology can be applied for calculating the individual or whole network losses. The basic idea is to breakdown the operation into sensitive equipments and to study the impact of voltage sags on the working of these devices. The sensitive equipments were four most commonly used industrial equipments namely:

1. Personal computers (PC)
2. Adjustable speed drives (ASD)
3. Programmable logic controllers (PLC)
4. Contactors

It was proposed that for knowing the exact number of process trips due to voltage sags, it is mandatory to have information about the common connection of above stated critical devices with each other.

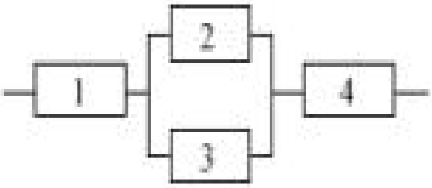


Fig. 4.1 Example of mutual connection of sensitive equipments arranged to form an industrial process [23].

Tripping of either one or combination of any of these devices may result in the shutdown of the whole industrial operation. So, these four sensitive devices were arranged in series or parallel combination to present industrial processes. Six typical configurations of sensitive equipments were considered for defining customer processes. Thirty seven diverse processes were developed using these six process configurations [24].

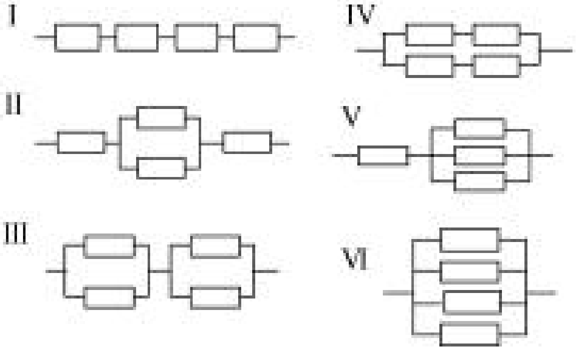


Fig. 4.2 Six characteristic configurations for industrial processes [24].

Accurate financial estimation of a process is done by precise counting of the sensitive equipment trips arranged in any of the block diagrams presented in the above Figure. The behavior of the individual equipment against voltage dips in the block diagram represents the response of the respective process. Therefore, the information of probability of tripping for every equipment and also of their joint connections can help in calculating the total probability of the whole process in case of voltage sag events. For example, the overall probability of tripping of a process represented by Figure 4.1 can be given by Equation [23]:

$$P_{trip} = 1 - (1 - p_1) \times (1 - p_2 . p_{23}) \times (1 - p_4) \qquad (4.2)$$

Where:

P_{trip} = Overall probability of process tripping against voltage dips.

p_1 = Probability of tripping of device 1.

p_2 = Probability of tripping of device 2.

p_3 = Probability of tripping of device 3.

p_4 = Probability of tripping of device 4.

The general expression for cumulative probability of the process is given by [23]:

$$P_{trip} = 1 - [\prod_{i=1} m \, (1 - \prod_{j=1} n \, p_{i,j})] \qquad (4.3)$$

Where:

m = No. of series connected equipment/groups of equipment.

n = No. of parallel connected equipment in the i^{th} equipment group.

$p_{i,j}$ = Cumulative probability of tripping of j^{th} equipment of the i^{th} serially connected equipment group.

4.1.3 UNCERTAINTY OF EQUIPMENT BEHAVIOUR

The performance of sensitive equipment during voltage sag is not the same every time. It has been experimented that the equipments which relate to specific equipment class show a variance in the sensitivity against voltage sags [7], [28]-[30]. This uncertainty about the voltage tolerance curve has been taken in to account in several research articles. Due to the different behavior shown by the equipments, the voltage tolerance curves may occur between the boundaries of the shaded region in the below Figure but the knee point of the characteristic curve should always be within the region C [5].

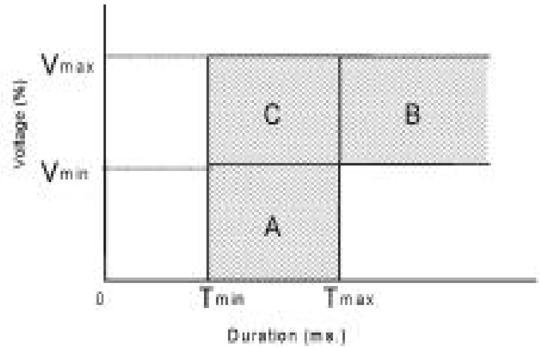


Fig. 4.3 Uncertainty region presented by shaded area [5].

The publications [5], [25] confer about the uncertainty involved in the tripping of these sensitive devices and compares two probability methods to materialize this effect in calculation of equipment trips due to voltage sags over a specific time interval. The two methods for finding the probability of tripping of critical devices are stated as:

a) Ordinary probability approach
b) Cumulative probability approach

(a) ORDINARY PROBABILITY APPROACH

In this method, characteristic curve of each device is taken separately and cumulative trip contribution is evaluated by adding the all the trip contributions made by a variety of possible sensitivity curves (uniform, moderate, high, low) for a specific equipment. It is then multiplied by probability of occurrence of trip of the respective equipment. [5]

$$f_{XY}(T,V) = f_X(T).f_Y(V) \qquad (4.4)$$

Where:

$f_X(T)$ = Probability density function for random variable T.

$f_Y(V)$ = Probability density function for random variable V.

$f_{XY}(T,V)$ = Joint probability density function for bi-variate random variable (T,V).

$$\mathrm{ENT}(\mathrm{T},\mathrm{V}) = f_{XY}(T,V).N(T,V) \qquad (4.5)$$

Where:

$\mathrm{ENT}(\mathrm{T},\mathrm{V})$ = Expected number of trips for specific equipment.

$N(T,V)$ = Tripping probability of individual equipment.

(b) CUMULATIVE PROBABILITY APPROACH

This method suggests that the possibility of equipment to trip or ride through any voltage sag event depends on the sensitivity of that particular device attained at that instant. It works on the principle of cumulative probability approach [5].

$$p_{XY}(T,V) = p_X(T).p_Y(V) \qquad (4.6)$$

Where:

$p_X(T)$ = Probability distribution function for random variable T.

$p_Y(V)$ = Probability distribution function for random variable V.

$p_{XY}(T,V)$ = Joint probability distribution function for bi-variate random variable (T,V).

$$\text{Total equipment trips} = \sum \mathrm{T} \sum \mathrm{V}\, p_{XY}(T,V).N(T,V) \quad (4.7)$$

Where:

N(T,V) = Number of voltage sags experienced at particular place over a definite period of time.

4.1.4 STOCHASTIC METHOD FOR CALCULATING THE PROBABILITY OF TRIPPING OF EQUIPMENTS

Publication [23] – [24] and [27] suggested probability density functions for finding the voltage sag sensitivity for the critical equipments. In this section, a method based on the stochastic estimation methodology presented in [37] for calculating the probability of tripping of sensitive equipments against the voltage dips is discussed and the same method has been adopted for calculation in this thesis. Tripping probability of sensitive devices is assessed by the normal distribution probability function.

The stochastic approach for calculating the equipment's sensitivity to voltage sags can be divided into following steps:

(1) Determine the uncertain area of voltage sensitivity curve for each sensitive equipment, divide the area into three regions as shown in the below Figure.

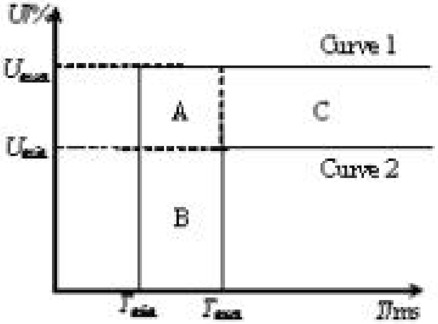


Fig 4.5 Voltage tolerance curve

U_{min} = minimal voltage magnitude of load voltage tolerance curve.

U_{max} = maximal voltage magnitude of load voltage tolerance curve.

T_{min} = minimal duration of load voltage tolerance curve.

T_{max} = maximal duration of load voltage tolerance curve.

Area above the curve 1 is the normal working area of the device in which it continues to operate successfully. The equipment will definitely trip whenever it experiences voltage dips having characteristic magnitude and duration falling under the area of curve 2. But this will not be the case if the voltage characteristics lie between curve 1 and curve 2. To find the probability of tripping of equipment under curve 1, this area has been divided in three regions A, B and C. The voltage tolerance curve is a singular function of stochastic variable U and T in the regions B and C respectively while it is a bi-variate function of variables U and T in the region A.

(2) Evaluate the probability density function which is a normal distribution function in this case. The input variables are T_{max}, T_{min}, U_{max}, U_{min}.The Equations for calculating the probability density function are stated below:

$$T_o = \frac{(T_{max} - T_{min})}{2} + T_{min} \qquad (4.12)$$

$$U_o = \frac{(U_{max} - U_{min})}{2} + U_{min} \qquad (4.13)$$

$$\sigma_1 = \frac{(T_o - T_{min})}{3} \qquad (4.14)$$

$$\sigma_2 = \frac{(U_o - U_{min})}{3} \qquad (4.15)$$

The probability model for area C is:

$$f_x(T) = \frac{1}{\sqrt{2\pi\sigma_1}} \exp\left[\frac{-(T - T_o)^2}{2{\sigma_1}^2}\right] \qquad (4.16)$$

The probability model unitary function for area B is:

$$f_y(U) = \frac{1}{\sqrt{2\pi\sigma_2}} \exp\left[\frac{-(U - T_o)^2}{2{\sigma_2}^2}\right] \qquad (4.17)$$

The probability model for bi-variable function area C is:

$$f_{x,y}(T, U) = \frac{1}{\sqrt{2\pi\sigma_1\sigma_2}} \exp\left\{-\frac{1}{2}\left[\frac{(T - T_o)^2}{{\sigma_1}^2} + \frac{(U - U_o)^2}{{\sigma_2}^2}\right]\right\} \qquad (4.18)$$

(3) After calculating the probability density functions, the probability of tripping of electrical devices can be assessed based on the following Equations:

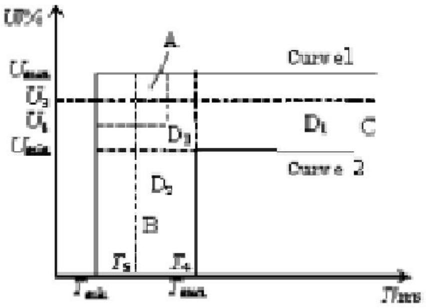


Fig. 4.6 Graph for calculating the probability of tripping of electrical devices [5].

Consider D_1 voltage sag event in the region C of the Figure 4.6. In this region only singular variable T is of considerable importance as sensitivity of the device is dependant of the duration of the voltage sag and independent of the voltage magnitude. The probability of tripping for voltage sag time duration T_1 ($T_{min} < T < T_1$) is calculated as:

$$p = \int_{T_{min}}^{T_1} f_x(T)dt \qquad (4.19)$$

For voltage sag event D2 having magnitude U_2 , lying in the region B according to Figure 4.4, the tripping probability for uni- variate variable U having boundary condition ($U_2 < U < U_{max}$) is:

$$p = \int_{U_2}^{U_{max}} f_y(U)du \qquad (4.20)$$

Consider voltage sag event D3 which falls in the region of A as depicted by Figure 4.6. The failure probability of the electrical equipment is dependent on two variables U (voltage sag magnitude) and T (voltage sag duration). The probability expression has double integral with boundary conditions ($T_{min} < T < T_3$) and ($U_3 < U < U_{max}$):

$$p = \int_{T_{min}}^{T_3} \int_{U_3}^{U_{max}} f_{x,y}\ (T, U)dudt \qquad (4.21)$$

4.1.5 EXAMPLES OF PROBABILITY TRIPPING CURVE OF EQUIPMENTS

For demonstration of the method defined above, the tripping probability curves of two sensitive equipments (PLC and contactor) are plotted below.

The areas in the characteristic curve of the contactors where there is uncertainty of the behavior of the device are marked as A, B and C as depicted by the Figure below:

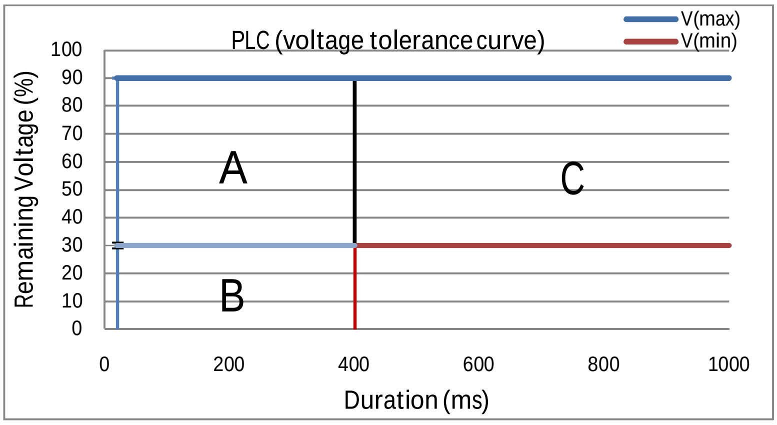


Fig. 4.7 PLC characteristic curve.

The normal distribution curve is taken for depicting the tripping probability.

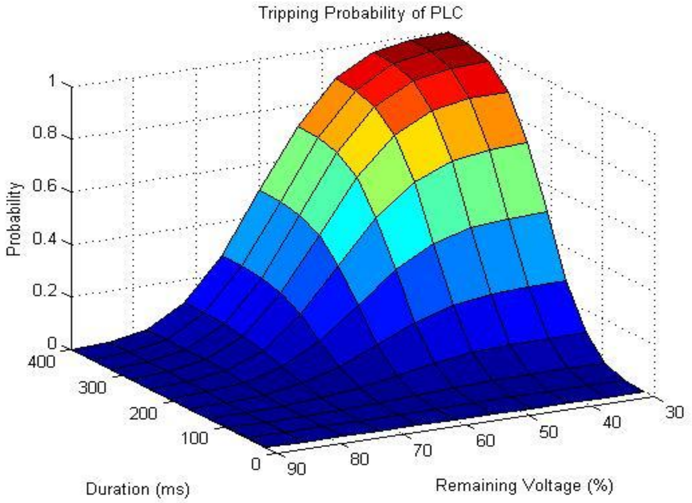


Fig. 4.8 Tripping probability of PLC in region A.

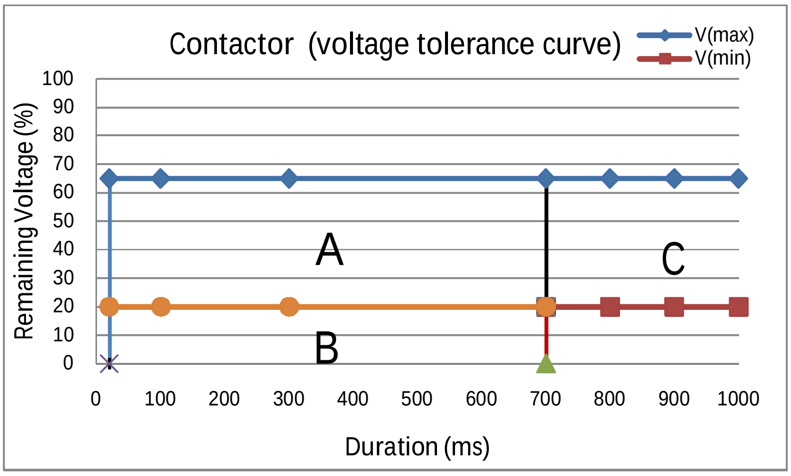


Fig. 4.9 Contactor characteristic curve.

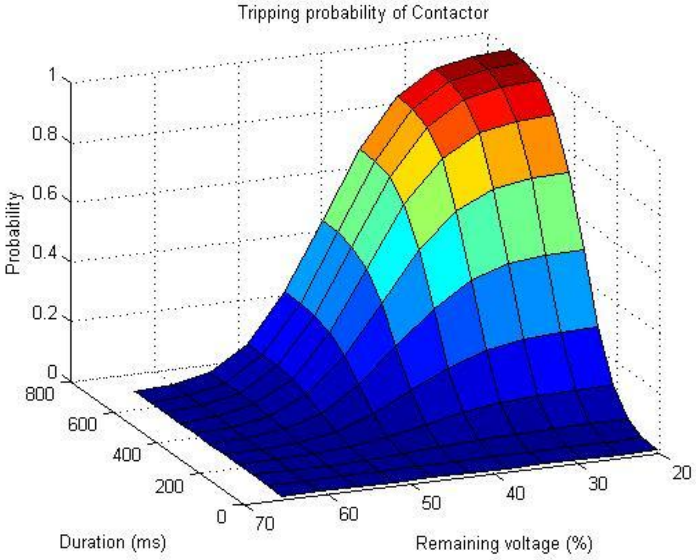


Fig. 4.10 Tripping probability of contacor in region A.

4.2 PROPOSED METHODOLOGY

This thesis proposes a novel approach for assessing the impact of voltage sag events on customer operations. The general idea of using specific devices for calculating the effect of voltage sags on a given process or customer has been utilized by authors [5], [23] - [24] and [27] but the current suggested assessment procedure has many distinct features which are discussed in section 4.2.2.

4.2.1 GENERAL CONCEPTS

A modular approach has been developed to evaluate the impacts of the voltage sag events on customer operations. This approach relies on the event tree technique and follows the basic concepts that have already been developed by authors for reliability assessment of automated distribution networks [33] - [34]. Susceptibility of customer operations against voltage sag events depends on the ride-through capabilities of its equipments against these events. Therefore, different failure modes of customer equipment during a voltage sag event should be considered in the related analysis. In the proposed approach, the sensitive equipments involved in the customer operations are identified. Normally, customer operations are accomplished based on the sequential operation of a set of these equipments. Therefore, the consequence of operational failure of the identified sensitive equipment on the customer operations is analyzed using the event tree method [35]. Using this approach, various possible consequences of a voltage sag event on customer operations are identified. By summing up the effects of each voltage sag event, the overall financial impact on the customer due to all voltage sag events is estimated.

4.2.2 DISTINGUISHING FEATURES OF PROPOSED APPROACH

Compared to previously developed evaluation techniques as cited in the section 4.1, the proposed technique is unique and has enormous differentiating aspects. Previously stated financial loss calculation procedures are meant for a specific group of industrial processes covering only limited customer operations and it cannot be applied for other customers but this suggested technique is based on the event tree methodology which makes it more comprehensive and adaptable for a variety of customers having different processes or operations. In former research papers, thirty seven industrial operations were modeled using the series/parallel combinations of the blocks consisting of sensitive devices but presented methodology can be applied for any number of industrial operations. Also in the presented method, the impact factors are assigned to each event tree outcome based on the contribution of sensitive devices in the operational failure of the process. So, there is no need for modeling specific processes based on series or parallel combination of sensitive devices. This makes it a general computation method and it can be modeled for any industrial, commercial or residential operation.

4.2.3 EVALUATION PROCEDURE

The evaluation procedure can be conducted according to the following steps:

(1) Sensitive equipments involved in the customer operations are identified. PLC, ASD, PC, SD and contactors are major sensitive devices that may involve in the customer operations.

(2) Susceptibility of the identified sensitive equipments against different voltage sag events is provided. The vulnerability of equipment against voltage sag events can be represented by a characteristic or tolerance curve. The characteristic curve represents the sensitivity of equipment to voltage sag events in terms of magnitude and duration of the sagged voltage. Characteristic curves for PLC, ASD, PC, SD and contactors are discussed in section 2.5.

(3) Considering the operational failures of the identified sensitive equipments, an event tree which reflects the customer operations is deduced. There are m^n possible outcomes for the deduced event tree, where m is the number of equipment operational status and n is the number of sensitive equipments involved in the analysis. For example, in the case of an industrial customer with five sensitive equipments, assuming two operational statuses for each equipment (one for normal operating status and the other for operational failure status), the

deduced event tree contains $2^5 = 32$ outcomes. The arrangement of different events defines the interdependency of sensitive equipment on one another.

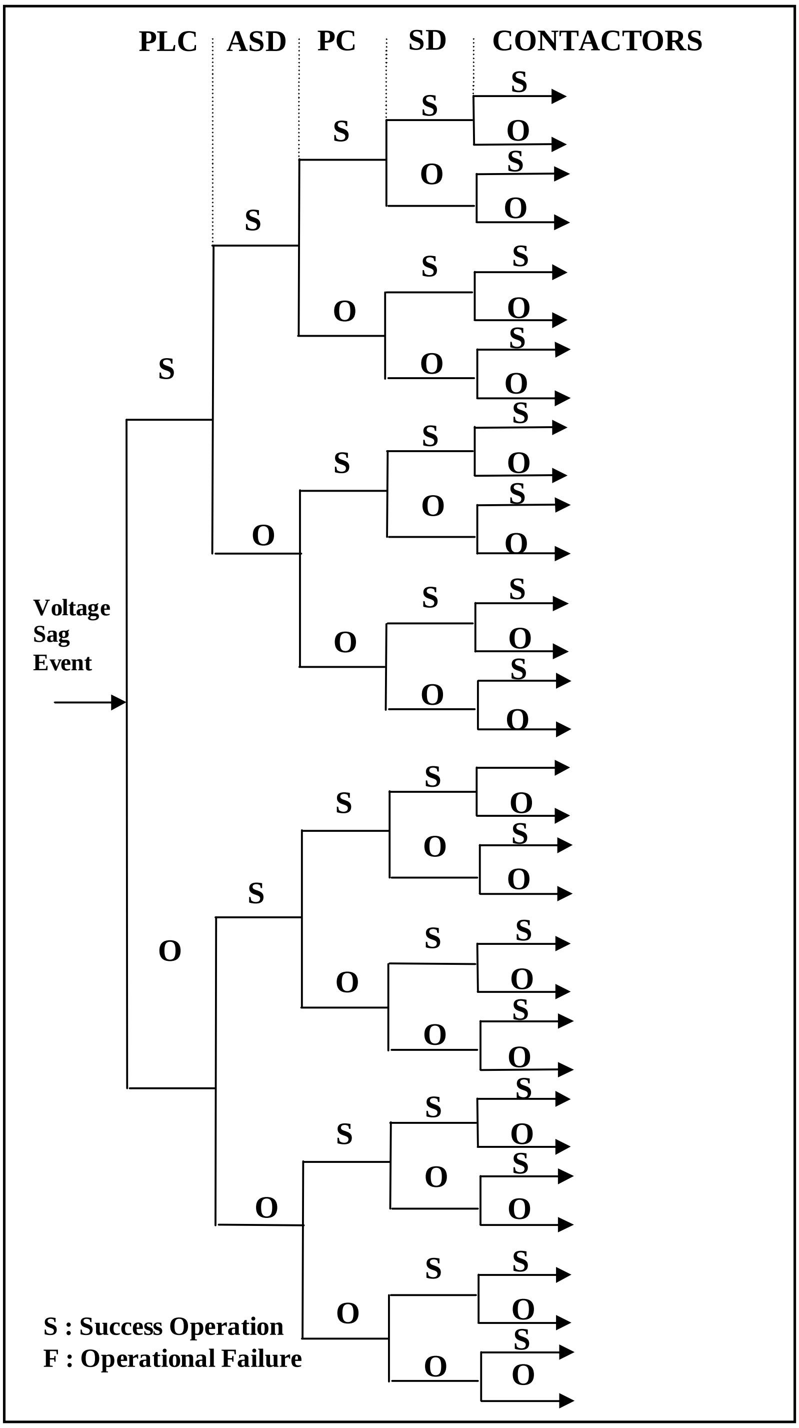


Fig. 4.4 event tree diagram for an operation having five critical devices.

(4) For each outcome of the deduced event tree, possible consequences on customer operations are examined. Each outcome of the event tree can then be assigned by a parameter designated as “impact factor”. Impact factor shows how the customer operations are disturbed when its sensitive equipments encounter an operational failure. It accommodates the effect of multiple number of same sensitive equipment involved in an operation. An impact factor should provide an estimate of the financial impact on the customer operations. Therefore, the numerical value assigned to the impact factor can be represented in per unit of the financial impact imposed on the customer due to a momentary power interruption by the following Equation:

$$\mathrm{IPF_j} = \frac{\mathrm{EOC_j}}{\mathrm{MIC}} \tag{4.8}$$

Where:

$\mathrm{IPF_j}$ = Impact factor of the event tree outcome number j.

$\mathrm{EOC_j}$ = Financial impacts on the customer operations corresponding to the event tree outcome number j

MIC = Financial impacts on the customer if it encounters with a momentary power interruption.

(5) The deduced event tree is analyzed for any possible modification. It might be possible to combine those event tree outcomes that result in the same impact factor. This will reduce the computation efforts of the next steps of evaluation procedures.

(6) Statistical data regarding the voltage sags events that the sensitive equipments of the customer may encounter during a specific period (e.g. one year) are provided. This data can be derived either using stochastic voltage sag prediction studies or power quality monitoring methods. References [1], [3] and [36] can be used for such purpose.

(7) The operational failure probabilities of the sensitive equipments involved in the customer operations are determined. Generally, the operational failure probability of any sensitive equipment against voltage sag events can be represented by the following expression:

$$f_{u,t}(U,T) = f_u(U)f_t(T) \qquad (4.9)$$

Where:

$f_{u,t}(U,T)$ = Probability of equipment malfunction when encountering a voltage sag event with remaining voltage equal to U and duration equal to T.

$f_u(U)$ = Probability of equipment malfunction when encountering a voltage sag event with remaining voltage equal to U.

$f_t(T)$ = Probability of equipment malfunction when encountering a voltage sag event with duration equal to T.

Usually, the normal distribution probability function is utilized for approximating the malfunction probability of sensitive equipments. The parameters of normal distribution probability functions have been taken from [37] and have been explained in the section 4.1.3.

(8) Contribution of voltage sag events on the financial losses imposed on the customer operations is determined. To perform this task, for the targeted voltage sag event, the probabilities of states involved in each outcome of the event tree are multiplied by each other. The result is then multiplied by impact factor corresponding to that event tree outcome (i.e. IPF_j) and MIC. This process is repeated for all the event tree outcomes. Finally, these results are summed up to find the contribution of the targeted voltage sag event on the financial losses imposed on the customer. The following Equation can be used for accomplishing this step:

$$\mathrm{VSIP_i} = \mathrm{MIC} \times \sum_{j=1}^{\mathrm{TNE}} \left\{ \mathrm{IPF_j} \times \bigcap_{m \in \mathrm{DN_j}} \mathrm{f}_{\mathrm{u,t}}^{\mathrm{m}}(\mathrm{U_i}, \mathrm{T_i}) \times \bigcap_{n \in \mathrm{UP_j}} \left(1 - \mathrm{f}_{\mathrm{u,t}}^{\mathrm{n}}(\mathrm{U_i}, \mathrm{T_i})\right) \right\} \tag{4.10}$$

Where:

$\mathrm{VSIP_i}$ = Contribution of the voltage sag event number i on the financial losses imposed on the customer.

$\mathrm{UP_j}$ = Set of sensitive equipment which are in the normal operating status for the event tree outcome number j.

$\mathrm{DN_j}$ = Set of sensitive equipment which are in the operational failure status for the event tree outcome number j.

$\mathrm{U_i}$ = Remaining voltage of the voltage sag event number i .

$\mathrm{T_i}$ = Duration of the voltage sag event number i.

$\mathrm{f}_{\mathrm{u,t}}^{\mathrm{x}}(\mathrm{U_i}, \mathrm{T_i})$ = Operational failure probability of equipment x, when encountering the voltage sag event number i with remaining voltage equal to U_i and duration equal to T_i.

TNE = Total number of the event tree outcomes.

(9) Overall financial impact on the customer due to all the voltage sag events during the study period is estimated by the following Equation:

$$\mathrm{VSC} = \sum_{i=1}^{\mathrm{TNS}} (\mathrm{VSIP_i} \times \mathrm{VSOR_i}) \tag{4.11}$$

Where:

VSC = Overall financial impact on the customer due to all the voltage sag events.

$VSOR_i$ = Occurrence rate of the voltage sag event number i during the study period.

TNS = Total number of voltage sag events.

4.3 OPTIMAL SELECTION OF MITIGATION SOULTIONS

4.3.1 OVERVIEW

Owing to the detrimental effects of the voltage sag on the customer processes, there is a need to cater with this problem, especially for the operations that are more susceptible to voltage dips. As the causes originating voltage sags cannot be eliminated completely, so the customers having critical and sensitive operations make use of the mitigation solutions to avoid any massive financial losses. These mitigation solutions tend to increase the ride through capabilities of the critical equipments or act as an alternative source of supply depending upon the type of mitigation solutions.

This thesis also proposes a procedure which can be used in the optimal selection of the mitigation solutions. Some basic economic terminologies are explained here for better understanding of the evaluation procedure.

4.3.2 ECONOMIC MEASURES

Two economic measures are used in this paper for optimal selection of voltage sag mitigation solutions. These measures are designated as “benefit cost ratio” and “payback period” are defined as follows:

4.3.2.1 BENEFIT COST RATIO (B/C)

This economic measure gives the economic feasibility of using any specific voltage sag mitigation solution. The benefit to cost ratio is calculated by the following Equation:

$$\mathrm{B/C} = \frac{(\mathrm{ACS}) \times (\mathrm{PWF}) \times (\mathrm{SLT})}{\mathrm{SIC} + \{(\mathrm{SOC}) \times (\mathrm{PWF}) \times (\mathrm{SLT})\}} \tag{4.22}$$

$$\mathrm{PWF} = \sum_{t=1}^{\mathrm{SLT}} (1 + p/100)^{-t} \tag{4.23}$$

Where:

ACS = Annual cost saved corresponds to the savings accumulated per year after employing a mitigation solution.

PWF = Present worth factor.

p = Annual interest rate, in percent.

t = Time period, in years.

SOC = Solution annual operating cost.

SIC = Solution investment cost.

SLT = Life time of the mitigation solution.

4.3.2.2 PAYBACK PERIOD (PP)

This economic measure shows the period (e.g. number of months) of benefits required for the project to break even. The payback period for a voltage sag mitigation solution is calculated by the following Equation:

$$PP = \frac{SIC \times 12}{(ACS - SOC)} \qquad (4.24)$$

Generally, a solution having the least payback period is the mostly preferred.

4.3.3 MITIGATION SOLUTION EVALUATION PROCEDURE

The evaluation procedure described in Section 4.2.4 can also be used for optimal selection of voltage sag mitigation solutions. The following procedure can be used for this purpose:

(1) The present status of the customer is considered as the base case. The steps 1 to 9, outlined in Section 4.2.4, are conducted in order to estimate the overall financial impact on the customer due to all the voltage sag events during the study period.

(2) Possible alternatives of the available voltage sag mitigation solutions (type, number and location) are provided based on the engineering judgments.

(3) One alternative of the possible options listed in the above step is selected. The characteristic or tolerance curves of the sensitive equipments which are protected by this option are modified according to the protection characteristics of the implemented devices.

(4) Steps 8 and 9, outlined in Section 4.2.4, are repeated in order to estimate the overall financial impact on the customer due to all the voltage sag events during the study period for present alternative.

(5) Net expenditure of the present alternative, which is the sum of all expenses required for design, purchase, installation and operation of the mitigation solution, is determined.

(6) Based on the results obtained from the above steps and using (4.22) and (4.24), the benefit cost ratio and payback period are calculated for present alternative.

(7) Steps 3 to 6 are repeated for all possible alternatives.

(8) Finally, the economic measures calculated for each alternative are compared with each other to find the optimal solution. Generally, a solution having the highest benefit-cost ratio and the least payback period is the most attractive one for employing but the practical viability of the solution has to be taken into account along with its financial impact.

CHAPTER 5

CASE STUDIES

5.1 OUTLINE

To illustrate the applicability of the proposed approach for quantitative assessment of voltage sag events on the customer operations, a typical case study for a semiconductor facility is discussed in this chapter. The reported momentary interruption cost for this facility is $1,400,000. The peak load of this facility is about 30 MW and its service voltage is 161 kV [15].

Although, as mentioned in chapter 1, cost associated with the voltage sag impact can be more than short interruption cost but here it is assumed that in case of worst voltage sag event, the financial impact is equal to interruption cost of the facility. Calculations have been performed for a specific customer operation of this facility which is estimated to have load of 500 kW. Out of this 500kW load, it is assumed that the consumption of sensitive equipment would be as shown in Table I.

Table I

DISTRIBUTION OF LOAD AMONG SENSITIVE EQUIPMENTS

PLC	**PC**	**ASD**	**Contactors**
10 %	18 %	65 %	7 %

Economic data of typical voltage sag mitigation solutions have been provided in Table II. When conducting the case study, it is assumed that the equipment level mitigation options (DPI, BC and CHD) and the control level mitigation option (UPS) are separately installed on each one of the targeted sensitive equipments. The plant level mitigation options (UPS and DVR) protect the whole targeted customer operations. A ten percent interest rate and 10 years of life time are assumed for the calculations.

TABLE II

ECONOMIC DATA ABOUT MITIGATION OPTIONS [11] - [15], [38]

Mitigation Option	**Investment cost (€/KVA)**	**Operating cost (% of the investment cost)**	**Threshold Voltage (% of remaining Voltage)**
Equipment Level Solution			
DPI	1960	-	-
BC	100	-	50
CHD	128 per device	-	25
Control Level Solution			
UPS	377	25	-
Overall Protection (Plant Level Solution)			
UPS	377	25	-
DVR	188.5	5	50

5.2 EVALUATION PROCEDURE FOR ASSESSING VOLTAGE SAG IMPACT

The evaluation procedure can be summarized in the following steps:

(1) PLC, ASD, PC and contactors are considered as sensitive equipments for the current customer operation.

(2) Characteristic curves for the above mentioned sensitive equipments have already been discussed in section 2.5 (chapter 2).

(3) The number of operation failure state of event tree for the process under consideration, based on four critical devices is $2^4 = 16$ outcomes of the event tree.

(4) Impact factors have been assigned to each event tree outcome.

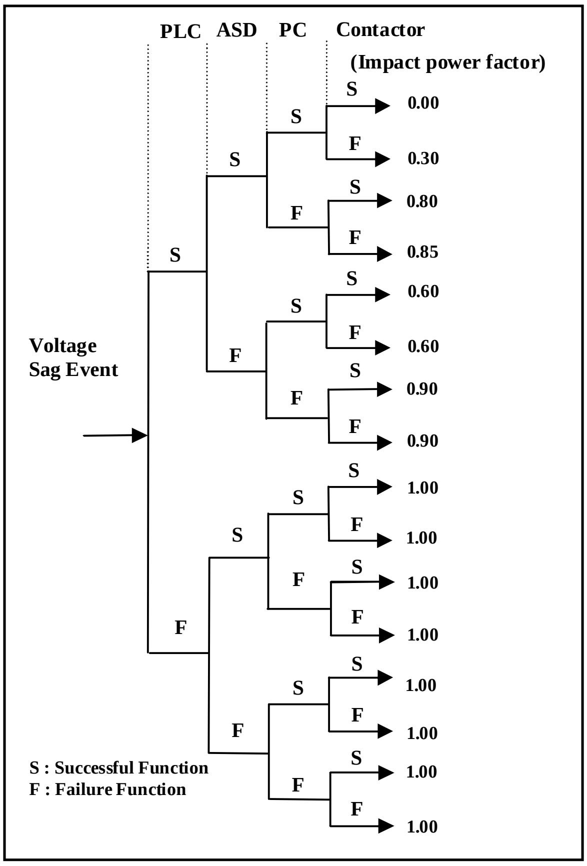


Fig. 5.1 Event tree diagram deduced for the case study.

(5) Event tree outcomes having same impact factors are modified and the new event tree diagram is formed.

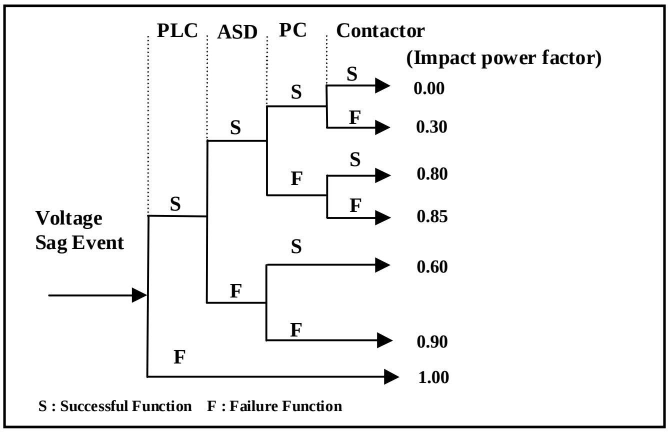


Fig. 5.2 Modified event tree diagram.

(6) Annual voltage sags statistical data based on a large power quality survey is used in this paper [39]. A simple and straight forward method of presenting voltage sags in terms of duration and magnitude is shown in table III [40].

TABLE III

ANNUAL NUMBER OF VOLTAGE SAG [39]

	Duration (ms)				
Voltage Magnitude	0-200	200-400	400-600	600-800	800-1000
81-90%	87	4	4	0	2
71-80%	16	2	1	1	0
61-70%	5	5	1	0	0
51-60%	6	2	0	0	0
41-50%	5	2	0	1	0
31-40%	1	1	0	0	0
21-30%	1	0	0	0	0
11-20%	2	1	0	1	0
0-10%	0	1	0	0	0

(7) For each voltage sag event, the operational failure probabilities of sensitive equipments are computed using the method described in [14]. The probabilities of event tree outcomes for each voltage sag event are determined. As an example, Figure 4 shows these probabilities for a sample voltage sag event with remaining voltage equal to 12 percent of the nominal voltage and duration equal to 50 milliseconds.

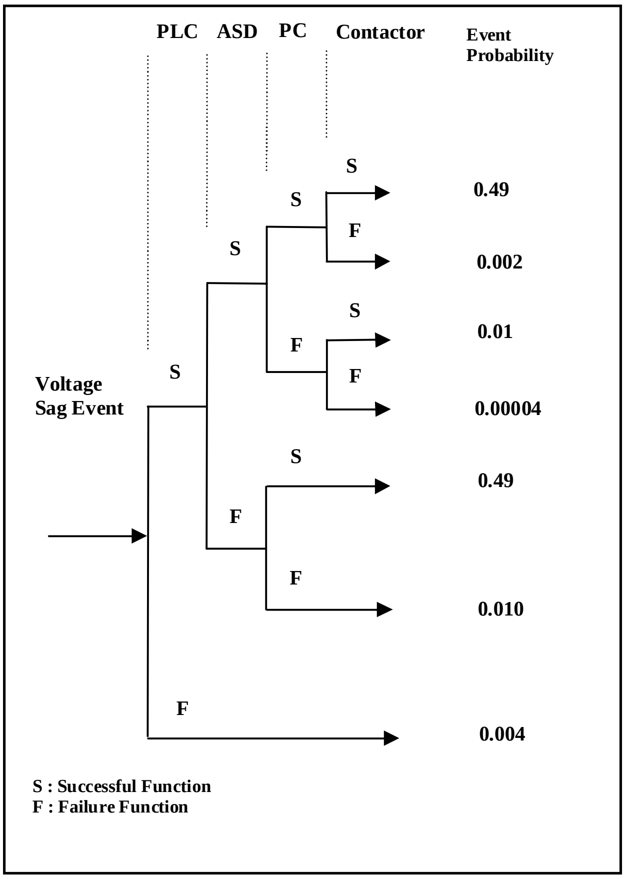


Fig. 5.3 Probabilities associated with the outcomes of the deduced event tree diagram for a sample voltage sag event.

(8) The contributions of each voltage sag event on the financial losses imposed on the customer operations are determined using (4.10). Table IV shows the contribution of all the voltage sag events, within the specified range, on the financial losses of the target customer operations.

TABLE IV

FINANCIAL IMPACT OF VARIOUS VOLTAGE SAGS ON THE CUSTOMER, EUR/YEAR

	Duration (ms)				
Voltage Magnitude	0-200	200-400	400-600	600-800	800-1000
81-90%	306	179	314	0	348
71-80%	12614	6459	6287	26	0
61-70%	12390	42943	7238	0	0
51-60%	15319	32181	0	0	0
41-50%	45456	33056	0	17152	0
31-40%	16082	16830	0	0	0
21-30%	16414	0	0	0	0
11-20%	19739	17558	0	17568	0
0-10%	0	16931	0	0	0

(9) The overall financial impact of the voltage sag events on the targeted customer operation is estimated using (4.11). This is equal to sum of all the contents of Table IV. The annual financial impact of the voltage sag events on the targeted facility operations is estimated to be around 353,390 Euro.

5.3 OPTIMAL SELECTION OF MITIGATION SOLUTIONS

The benefit-cost ratio and payback period have been calculated for various voltage sag mitigation options using the methodology described in 4.2.2. The results are shown in Figures 5.4 – 5.8.

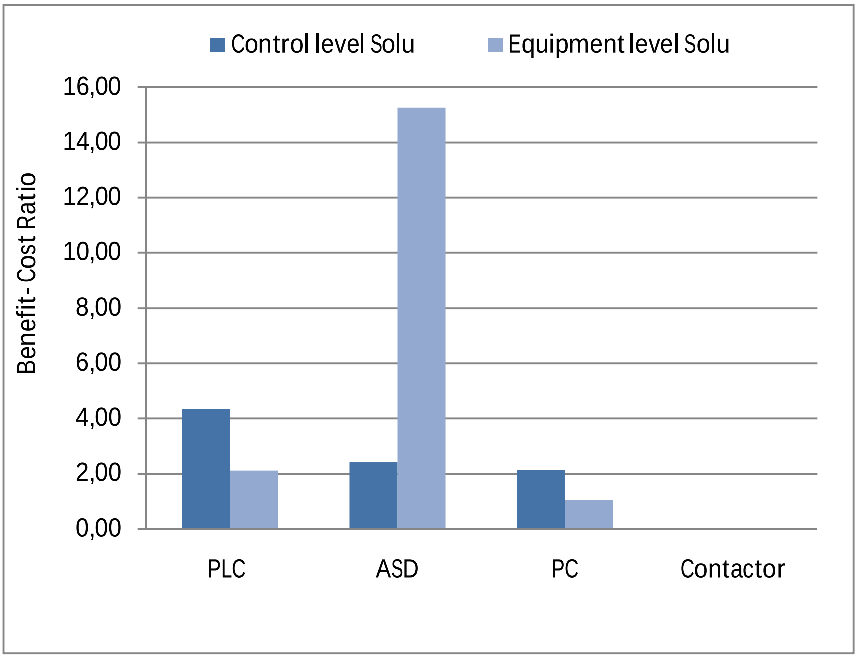


Fig. 5.4. Benefit-cost ratio when protecting one sensitive equipment.

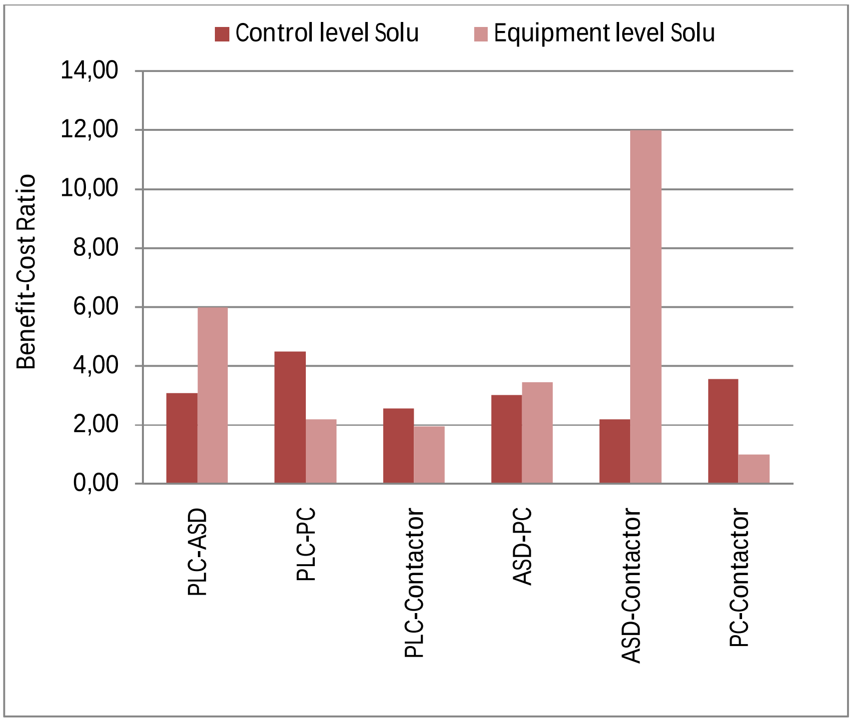


Fig. 5.5. Benefit-cost ratio when protecting two sensitive equipments.

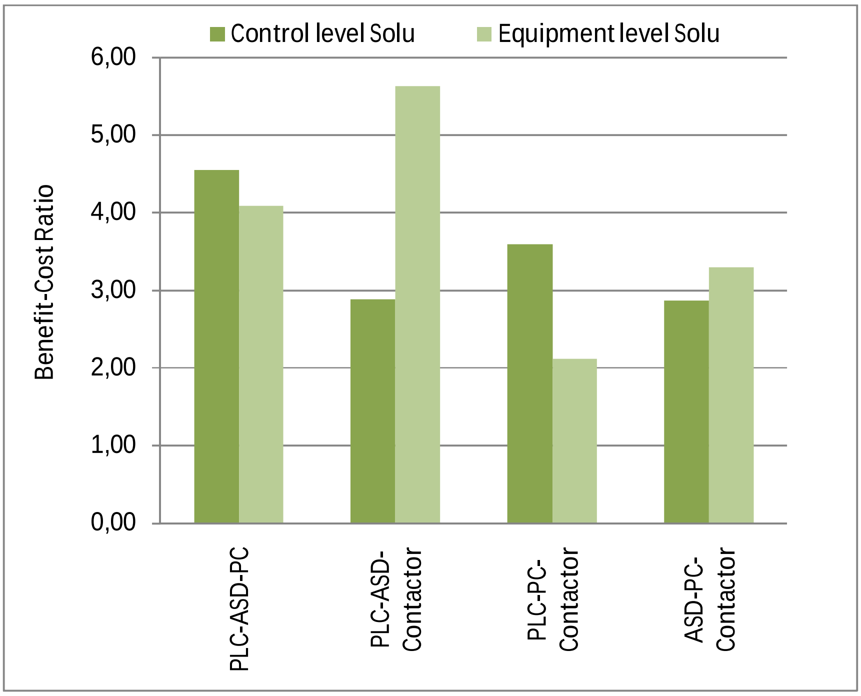


Fig. 5.6. Benefit-cost ratio when protecting three sensitive equipments.

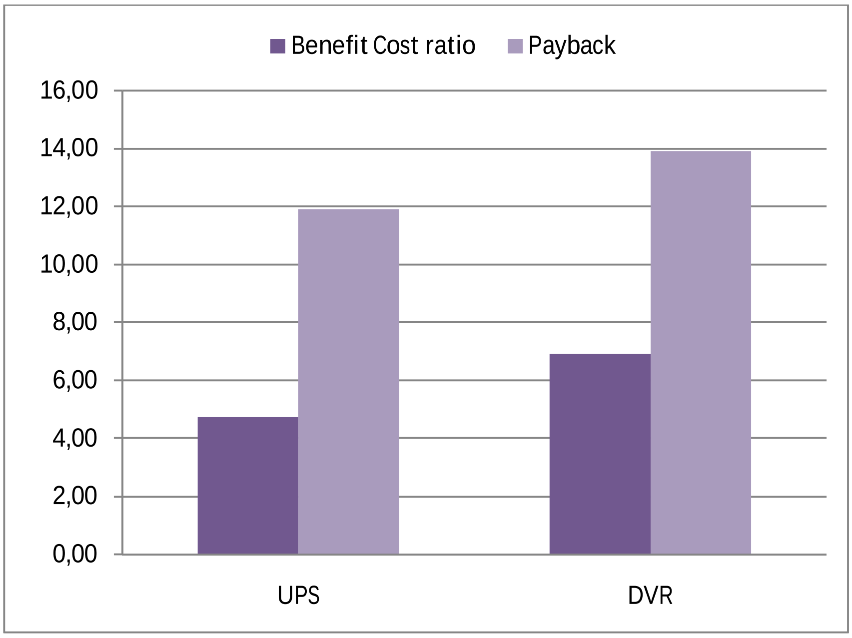


Fig. 5.7. Benefit-cost ratio and pay back period for plant level solutions.

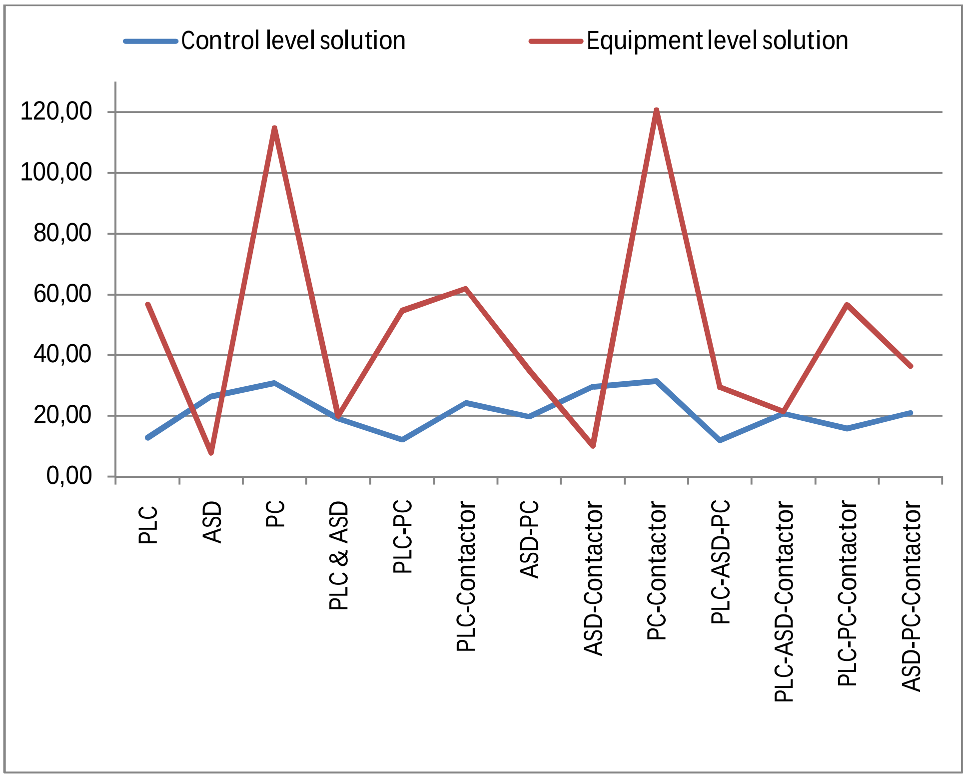


Fig. 5.8. Pay back period for various mitigation options.

The payback period of mitigation options vary on each level as shown in Fig. 5.8. The cost of mitigation options increases drastically from equipment level solution to the plant level solutions. In this particular case study, control level solutions are the most economically viable solutions having the least payback period but it requires regular testing and maintenance. In few cases, the equipment level solutions can be economical as well but the main drawback is the requirement of comprehensive information of the target device where solution is to be utilized. Most of the customers are not that much well aware of the details of working of their equipments and also in majority of the cases the manufacturing company prohibits the installation of mitigation solution which can alter the original design of the equipments [15]. It should be noted that the results of this case study are not generic and depend on the nature of the customer operations and contribution of sensitive devices in these operations.

5.4 SENSITIVITY ANALYSIS

There is a diverse range of downtime costs among different industries as all the industries are not same sensitive to the effect of voltage sag events. Therefore, the cost of momentary interruptions varies significantly. It mainly depends on the nature of the manufacturing process and sensitivity of the process equipments. For example amount of losses can range from high values such as \$54000 per megawatt for a semiconductor industry to small values such as \$2000 per megawatt for a plastic extrusion and pulp and paper processes [17]. To find the impact of this parameter on the optimal solution for mitigation of voltage sags, the calculations have been performed based on the proposed methodology for comparative assessment of feasibility of different mitigation options for semiconductor industry and plastic extrusion pulp and paper industry with above mentioned momentary interruption cost. Figures 5.9 and 5.10 show the results. As it can be seen from the results presented in these Figures, the mitigation solutions are feasible only for a industry which has high interruption cost.

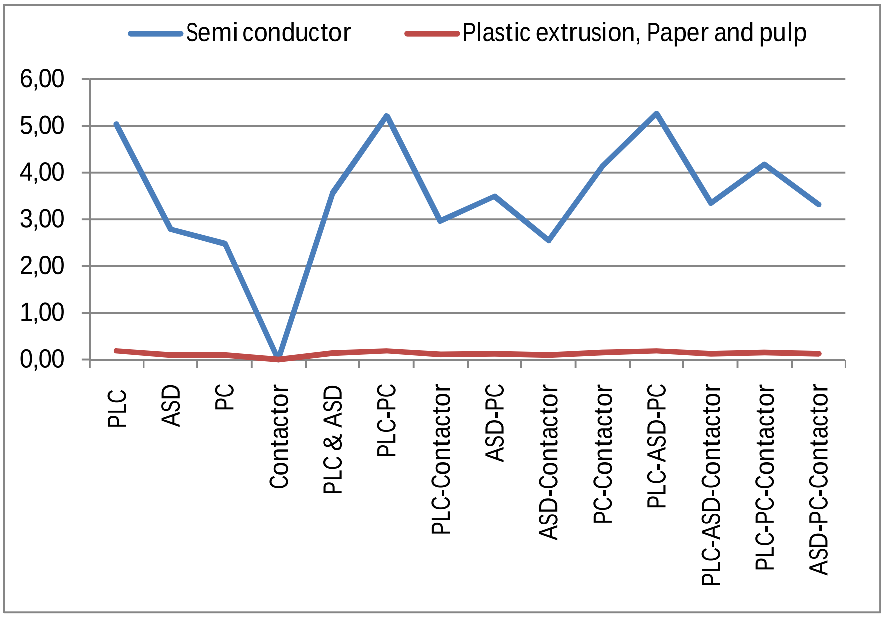


Fig. 5.9. Benefit-cost ratio when employing control level mitigation solutions for semi-conductor and plastic extrusion, paper and pulp industries.

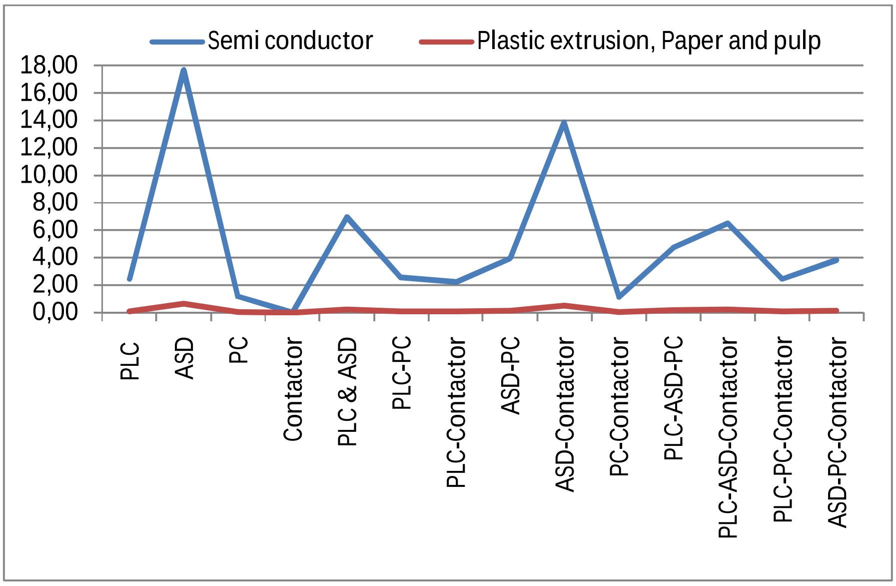


Fig. 5.10. Benefit-cost ratio when employing equipment level mitigation solutions for semi-conductor and plastic extrusion, paper and pulp industries.

CHAPTER 6

CONCLUSION

When the susceptibility of the consumer operations is increasing to the voltage sags, power distribution companies and also the customer should have comprehensive understanding of the effect of voltage sags in their premises. The scope of this thesis lies in the area of voltage sags and suggests an estimation method based on event tree methodology for assessing the impact of voltage sag events on the consumer operations.

Following are the contributions made by the thesis:

- A simple but comprehensive novel assessment procedure for calculating the impact of voltage sag events on consumer operations.
- Using this methodology, it is possible to estimate the financial losses resulting from malfunctioning of sensitive equipments due to voltage sag events.
- It can also be applied for the assessing the applicability of various voltage sag mitigation options from cost-effectiveness point of view.
- The purposed evaluation procedure is generic and can be applied on diverse customer processes.

The proposed methodology differentiates from the previously developed assessment methods as the current technique is not limited to specific customer operations. It is more comprehensive and adaptable for various consumer operations. It can be modeled for any industrial, commercial or residential operation for assessing the impact of voltage sag events.

For demonstration of the proposed technique, a typical case study was discussed in the paper for a semiconductor industry. The impacts of various voltage sag events on the facility concerned in this case study were evaluated. In addition, the applicability of various voltage sag mitigation solutions was studied through comparative assessment. The effects of momentary interruption cost on the feasibility of mitigation solutions were studied as well.

The main area of focus of this thesis is estimation of economic losses incurred due to malfunction of the processes against voltage sags. In future, the same method can be modeled for making the voltage tolerance curves for residential, commercial and industrial consumers which can help in voltage sag analysis on a broader scale that can be used as an important element in a comprehensive power system analysis by the power distribution networks. As presented by the thesis, the calculations show that there is a high economic impact of voltage sags on the sensitive customers and high financial losses are suffered annually due to it. This gives out the option of customized mitigation solution for the voltage sag events to the sensitive consumer, who are possibly not in very large quantity.

REFERENCES

[1] M Math H. J. Bollen, *Understanding Power Quality Problems, Voltage Sags and Interruptions*, New Jersey, USA, IEEE Press, 1999.

[2] F. Martzloff, Power quality work at International Electrotechnical Commission, PQA-97 Europe, June 1997, Stockholm, Sweden, Elforsk: Stockholm, Sweden.

[3] P. Heine, “Voltage sags in power distribution networks,” Ph.D. Dissertation, Department of Electrical Engineering, Aalto University School of Science and technology, Espoo, Finland, 2005.

[4] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Standard 1159, New York, 2009.

[5] C. P. Gupta and J. V. Milanović, “Probabilistic methods for counting equipment trips due to voltage sags,” in *Proc. 9th International Conference on Probabilistic Methods Applied to Power Systems, 11-15 June 2006, KTH, Stockholm, Sweden.*

[6] Heine, P., Lehtonen, M., “Voltage Sags Caused by Faults at Different Power System Levels and Experienced by Low Voltage Customers”, PMAPS 2002, *The 7th International Conference of Probabilistic Methods Applied to Power Systems, Naples, Italy, September 22-26, 2002, pp. 563-568.*

[7] P. Pohjanheimo, “A probabilistic method for comprehensive voltage sag management in power distribution systems,” Ph.D. Dissertation, Department of Electrical Engineering, Aalto University School of Science and Technology, Espoo, Finland, 2003.

[8] T.S. Key, Diagnosis power quality related computer problems, *IEEE Transaction on Industry Application*, vol. 15, no. 4, July 1979, pp. 381-393.

[9] Specification for semiconductor processing equipment voltage sag immunity, SEMI F47-0200 [online]. Available: http://f47testing.epri.com/f47abstract.html.

[10] C. P. Gupta, K. Stockman and J. V. Milanović, “Sensitivity of personal computers to voltage sags and short interruptions,” IEEE Transaction on Power Delivery, Vol. 21, No. 2, April 2006.

[11] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power System Quality*, Mcgraw Hill, New York, Second Edition, 2003.

[12] Power Quality Solution Inc. [online]. Available: http://www.pqsi.com/coillocks.html.

[13] K. Stockman, F. D'hulster, M. Didden, R. Belmans, “Embedded solution to protect textile processes against voltage sags”, in Proc. 37th IEEE-IAS Annual Meeting, 10 December 2002, pp. 2561-2566.

[14] Voltage-Dip Proofing Inverters [online]. Available: http://measurelogic.com/Resources/DPI52-SeriesManual1.0ml.pdf.

[15] “Technical and Economic Considerations for Power Quality Improvements,” Final Report, EPRI 1005910, Palo Alto, CA, 2001.

[16] W. Solter, “A new international UPS classification by IEC 62040-3”, *Telecommunication Energy Conference, 10 December 2002.*

[17] S. Karve, “Three of a kind [UPS topologies, IEC standard]” *IEE Review, Vol. 46, Issue 2, March 2000.*

[18] P. Daehler and R. Affolter, “Requirements and solutions for dynamic voltage restorers”, IEEE Power Engineering Society Winter Meeting, Singapore, 2000.

[19] Whisenant S.G., “DVRs provide quality power to critical customers”, *Transmission and Distribution World, December 1997.*

[20] IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment, IEEE Standard 1346-1998, May 1998.

[21] ITI (CBEMA) Curve (Revised 2000), [online]. Available: http://www.itic.org/clientuploads/Oct2000Curve.pdf

[22] S. C. Vegunta and J. V. Milanović, “Estimation of cost of downtime of industrial process due to voltage sags”, *IEEE Transaction on Power Delivery, 31 December 2009.*

[23] C. P. Gupta and J. V. Milanović, “Probabilistic assessment of financial losses due to interruptions and voltage sags—Part I: The Methodology”, *IEEE Transaction on Power Delivery, Vol. 21, No. 2, April 2006.*

[24] C. P. Gupta and J. V. Milanović, “Probabilistic assessment of financial losses due to interruptions and voltage sags—Part II: The Methodology”, *IEEE Transaction on Power Delivery, Vol. 21, No. 2, April 2006.*

[25] J. Y. Chan, J. V. Milanović, “Methodology for assessment of financial losses due to voltage sags and short interruptions”, *9th International Conference on Electrical Power Quality and Utilisation, 2007.*

[26] J. Y. Chan, J. V. Milanović, “Methodology for development of customized customer damage functions for evaluation of financial losses due to voltage sags and interruptions”, Power Tech., IEEE Bucharest, 2009.

[27] C. P. Gupta and J. V. Milanović, “Probabilistic assessment of equipment trips due to voltage sags”, *IEEE Transaction on Power Delivery, Vol. 21, No. 2, April 2006.*

[28] E. Collins and M. Bridgwood, "The impact of power disturbances on AC-coil contactors", *Proc. IEEE Textile, Fiber and Film Industry Technical Annual Conference, Greenville, USA, 6-8 May 1997.*

[29] S. Z. Djokic, J.V. Milanovic and D.S. Kirschen, "Sensitivity of AC coil contactors to voltage sags, short interruptions and under-voltage transients", *IEEE Transactions on Power Delivery, Vol 19, No. 3, 2004, pp. 1299- 1307.*

[30] S. Z.Djokic, “Generalized methodology for the assessment of voltage sag performance indices and equipment sensitivity”, PhD Thesis, UMIST, Manchester, UK, April 2004.

[31] B.W Kennedy , P*ower Quality Primer*, New York, McGraw Hill, 2000,

[32] *Power Quality: Customer Financial Impact/Risk Assessment Tool,* BC Hydro, BC, Canada, A04-587b, 2005.B.

[33] S. Kazemi, M. Fotuhi–Firuzabad, and R. Billinton, "Reliability assessment of an automated distribution system," *IET Generation, Transmission and Distribution, vol. 1, pp. 223-233, March 2007*.

[34] S. Kazemi, M. Fotuhi–Firuzabad, M. Sanaye-Pasand, and M. Lehtonen, "Impacts of automatic control systems of loop restoration scheme on the distribution system reliability," *IET Generation, Transmission and Distribution, vol. 3, pp. 891-902, October 2009*.

[35] R. Billinton, and R. N. Allan, *Reliability Evaluation of Engineering Systems*, Plenum Press, Second Edition, 1992.

[36] Roberto Chouhy Leborgne, “Voltage sag characterization and estimation,” Licentiate Dissertation, Department of Energy and Environment, Division of Electrical Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2005.

[37] Xianyong Xiao, Xuna Liu and Honggeng Yang “Stochastic estimation trip frequency of sensitive equipment due to voltage sag”, *IEEE Asia Pacific Conference, December 2008.*

[38] A Mark Mcgranaghan and Bill Roettger, “Economic evaluation of power quality”, *IEEE Power Engineering Review, February 2002*.

[39] Roberto Chouhy Leborgne, “Voltage sag characterization and estimation,” Licentiate Dissertation, Department of Energy and Environment, Division of Electrical Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2005.

[40] L.E. Conrad and Math H.J. Bollen, “Voltage sag coordination for reliable plant operation”, *IEEE Transactions on Industry Applications, vol. 33, no. 6, November 1997, pp.1459-1464*.

[41] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, IEEE Standard 493-2007, July 2007.

APPENDIX A

Voltage Sag Data

Voltage sag survey on a distribution feeder of 13.8 KV [39].

Date	Retained voltage (%)	Duration (ms)
30/04/2002@17:47:05,133	88	8
03/05/2002@19:59:07,797	87	108
03/05/2002@19:59:10,922	89	467
03/05/2002@19:59:11,297	84	892
03/05/2002@20:00:01,938	83	517
03/05/2002@20:00:36,130	89	8
03/05/2002@20:03:15,318	89	25
07/05/2002@15:00:49,921	88	58
13/05/2002@11:44:36,516	83	33
19/05/2002@10:14:47,201	73	25
19/05/2002@10:24:48,236	89	41
21/05/2002@03:55:51,739	88	8
12/06/2002@05:11:02,615	85	358
12/06/2002@06:04:21,416	88	500
17/07/2002@07:35:26,046	89	33
17/07/2002@07:35:26,054	81	41
27/07/2002@07:58:41.924	84	41
29/07/2002@14:50:23,319	39	175
01/08/2002@23:10:43,611	70	266
01/08/2002@23:32:34,540	88	16
02/08/2002@12:56:06,179	70	307
02/08/2002@23:18:06,356	70	283
03/08/2002@10:59:49,981	81	16
04/08/2002@06:40:37,418	86	108
04/08/2002@13:26:50,374	68	250
06/08/2002@10:41:28.942	90	341
09/08/2002@15:03:15.261	80	41
09/08/2002@15:03:17.760	71	526
09/08/2002@15:03:20.217	70	491
09/08/2002@19:10:44.346	82	125
26/08/2002@18:17:26.380	89	33

APPENDIX A (contd.)

26/08/2002@18:17:28.564	86	42
26/08/2002@18:38:10.649	87	33
30/08/2002@02:17:46.953	87	41
06/09/2002@13:45:07.255	89	83
06/09/2002@19:28:40.893	77	100
06/09/2002@19:28:45.116	88	8
07/09/2002@03:22:40.736	82	41
07/09/2002@03:47:08.028	73	274
07/09/2002@03:56:16.495	58	33
07/09/2002@03:56:23.045	53	50
07/09/2002@03:56:37.217	39	225
07/09/2002@03:58:04.859	88	8
07/09/2002@03:59:36.364	88	8
07/09/2002@05:27:31.638	88	83
07/09/2002@05:58:59.848	89	16
07/09/2002@10:29:52.366	89	83
10/09/2002@14:25:06.805	88	8
14/09/2002@10:55:33.598	89	16
22/09/2002@11:52:16.395	88	8
29/09/2002@23:16:52.778	84	208
29/09/2002@23:29:37.507	84	41
01/10/2002@11:34:14.952	87	33
01/10/2002@11:34:21.304	78	25
01/10/2002@11:34:34.873	89	25
02/10/2002@16:07:46.578	28	191
02/10/2002@16:08:47.421	52	25
09/10/2002@09:02:17.733	78	17
13/10/2002@06:42:39.683	67	41
13/10/2002@06:42:41.866	62	242
13/10/2002@06:42:43.882	43	124
13/10/2002@06:42:43.890	19	133
13/10/2002@06:46:07.354	54	41
13/10/2002@06:46:25.175	78	751
14/10/2002@14:11:15.955	86	33
15/10/2002@11:43:48.323	73	41
22/10/2002@00:35:10.786	86	8
25/10/2002@20:54:41.023	88	16

APPENDIX A (contd.)

27/10/2002@23:38:49.016	84	124
27/10/2002@23:38:51.107	84	33
27/10/2002@23:38:53.356	85	66
28/10/2002@14:20:10.026	84	16
28/10/2002@14:32:21.382	88	8
28/10/2002@14:37:59.658	86	8
28/10/2002@14:38:55.146	84	24
28/10/2002@15:45:13.101	88	74
28/10/2002@17:17:24.554	83	16
28/10/2002@19:10:36.002	89	8
29/10/2002@08:47:47.527	19	374
29/10/2002@23:28:58.172	12	50
10/11/2002@07:01:33.826	41	66
10/11/2002@08:31:20.532	50	683
15/11/2002@08:44:22.260	84	41
19/11/2002@07:58:29.741	89	8
21/11/2002@12:11:03.534	88	41
28/11/2002@09:51:22.499	20	676
02/12/2002@15:01:31.271	89	66
03/12/2002@14:13:14.876	85	33
03/12/2002@14:13:20.900	85	33
03/12/2002@14:13:33.416	85	125
03/12/2002@20:16:23.202	88	25
03/12/2002@20:38:01.465	77	41
03/12/2002@20:39:16.766	85	33
04/12/2002@16:47:19.630	86	16
04/12/2002@16:51:15.519	89	8
05/12/2002@16:54:46.196	85	33
09/12/2002@10:04:30.876	5	233
10/12/2002@00:58:14.887	85	66
13/12/2002@17:19:49.705	87	375
13/12/2002@19:28:50.180	89	116
16/12/2002@16:33:48.405	88	183
16/12/2002@16:33:48.921	84	416
20/12/2002@13:08:04.212	75	25
24/12/2002@09:49:44.187	81	33

APPENDIX A (contd.)

29/12/2002@16:52:59.156	57	50
29/12/2002@16:53:01.371	52	216
29/12/2002@16:53:03.420	46	141
17/01/2003@19:26:08.085	78	33
18/01/2003@11:02:56.733	77	50
18/01/2003@11:03:14.740	84	49
21/01/2003@01:14:03.341	80	91
22/01/2003@13:08:37.338	87	8
27/01/2003@17:29:42.013	86	16
30/01/2003@18:36:15.122	84	91
30/01/2003@18:36:15.130	82	1007
30/01/2003@20:54:11.114	89	91
01/02/2003@18:49:39.081	89	8
02/02/2003@17:06:14.839	86	33
02/02/2003@17:29:15.444	84	33
06/02/2003@17:21:24.394	88	7
06/02/2003@17:57:44.323	61	50
16/02/2003@15:25:10.936	87	8
16/02/2003@15:25:13.153	88	16
16/02/2003@15:25:15.346	89	8
17/02/2003@16:04:54.384	83	41
19/02/2003@01:14:29.651	88	24
22/02/2003@13:06:09.463	64	50
22/02/2003@13:06:12.037	73	308
22/02/2003@13:36:05.849	56	41
22/02/2003@13:36:08.109	53	300
22/02/2003@13:36:10.251	43	208
22/02/2003@13:37:44.386	79	24
26/02/2003@11:41:04.220	88	8
04/03/2003@15:54:26.801	50	41
04/03/2003@15:54:28.727	49	49
04/03/2003@15:54:30.902	49	233
05/03/2003@00:59:44.399	77	24
05/03/2003@02:12:19.687	76	16
13/03/2003@15:32:42.863	89	74

APPENDIX A (contd.)

13/03/2003@15:32:47.552	86	16
17/03/2003@11:03:35.727	84	49
22/03/2003@17:42:12.185	70	25
29/03/2003@17:34:16.539	87	16
30/03/2003@08:52:25.672	86	33
04/04/2003@10:05:15.096	87	41
15/04/2003@11:24:52.627	89	8
16/04/2003@09:17:15.708	67	33
16/04/2003@09:17:17.924	89	8
02/05/2003@15:41:34.690	87	8
05/05/2003@06:12:23.031	77	16
02/05/2003@15:41:34.690	87	8
05/05/2003@06:12:23.031	77	16

APPENDIX B

Comparative assessment of mitigation devices.

Sensitive equipment **0.5MW**

Rate 40,716 €/KW

Base Case Interruption Cost 409506 (1 Year)

Sensitive equip. 500 **KW**

	Solutions	Total Momentary int cost	Cost Saved (1 Year)	Cost Saved (10 Years)	Initial Cost	operational Cost	Net Expenditure	benefit Cost ratio	Pay Back (Months)
UPS On One Device	1	**370331**	39175,1394	240692	**18850**	28954	47804	**5,04**	10,68
	2	**268554**	140951,57	866006	122525	188198	310 723	**2,79**	21,69
	3	**374765**	34740,2378	213444	33930	52116	86046	**2,48**	25,24
	4	**409458**	47,5883484	292	13195	20268	33463	**0,01**	79,27
UPS On Two Devices	1	**201708**	207797,673	1276709	141375	217152	358 527	**3,56**	16,01
	2	**295994**	113511,756	697416	52780	81070	133 850	**5,21**	10,28
	3	**370306**	39199,3419	240841	32045	49221	81266	**2,96**	20,07
	4	**184177**	225328,626	1384419	156455	240315	396 770	**3,49**	16,41
	5	**266674**	142831,715	877558	135720	208466	344 186	**2,55**	24,34
	6	**374739**	34766,7148	213607	47125	4548	51673	**4,13**	27,05
UPS On Three Devices	1	**27995**	381511,171	2344005	175305	269268	444 573	**5,27**	10,14
	2	**196178**	213327,524	1310684	154570	237420	391 990	**3,34**	17,28
	3	**295962**	113543,52	697611	65975	101338	167 313	**4,17**	13,28
	4	**176703**	232803,127	1430342	169650	260582	430 232	**3,32**	17,40
Embedded Solution On One Device	1	**370331**	39175,1394	240692	98020	0	98020	**2,46**	48,87
	2	**315902**	93603,8682	575102	32500	0	32500	**17,70**	6,78
	3	**374765**	34740,2378	213444	176436	0	176 436	**1,21**	99,19
	4	**409471**	34,5686548	212	8972,6	0	8973	**0,02**	5069,51
Embedded Solution On Two Devices	1	**261723**	147782,388	907975	130520	0	130 520	**6,96**	17,25
	2	**295994**	113511,756	697416	274456	0	274 456	**2,54**	47,22
	3	**370320**	39185,3594	240755	106992,6	0	106 993	**2,25**	53,33
	4	**274279**	135226,704	830833	208936	0	208 936	**3,98**	30,18
	5	**315743**	93762,9395	576080	41472,6	0	41473	**13,89**	8,64
	6	**374755**	34750,5288	213507	185408,6	0	185 409	**1,15**	104,21
Embedded Solution On Three Devices	1	**172759**	236746,927	1454573	306956	0	306 956	**4,74**	25,32
	2	**261362**	148143,756	910195	139492,6	0	139 493	**6,53**	18,39
	3	**295984**	113522,132	697480	283428,6	0	283 429	**2,46**	48,76
	4	**273932**	135573,817	832966	217908,6	0	217 909	**3,82**	31,39
Embedded Solution On Four Devices	1	**171957**	237548,768	1459500	315928,6	0	315 929	**4,62**	25,98
DVR	1	**251210**	158295,866	972570	94250	27135	121 385	**8,01**	11,96
UPS	2	**0**	409505,681	2516003	188500	271346	459 846	**5,47**	10,08

APPENDIX C

Mat lab code for calculation of tripping probability for uni-variate variable T.

```
function probabt(t,T,u,U)
To = (T-t)/2 + t;
Uo = (U-u)/2 + u;
sigma_1 = (To-t)/3;
sigma_2 = (Uo-u)/3;
F = @(T_user)(1/(sqrt(2*pi).*sigma_1).*exp(-(T_user-
To).^2./(2*sigma_1.^2)));
repeat=1;
while repeat
T_user = input ('Enter t:');
Q = quad(F,t,T_user)
repeat = input ('Do you want another calc? 1=yes 0=no');
end
end
```

Mat lab code for calculation of tripping probability for uni-variate variable T.

```
function probabv(t,T,u,U)
To = (T-t)/2 + t;
Uo = (U-u)/2 + u;
sigma_1 = (To-t)/3;
sigma_2 = (Uo-u)/3;
F = @(U_user)(1/(sqrt(2*pi).*sigma_2).*exp(-(U_user-
Uo).^2./(2*sigma_2.^2)));
repeat=1;
while repeat
U_user = input ('Enter u:');
Q = quad(F,U_user,U)
repeat = input ('Do you want another calc? 1=yes 0=no');
end
end
```

APPENDIX C (contd.)

Mat lab code for calculation of tripping probability for bi-variate variable U and T.

```
function probab(t,T,u,U)
To = (T-t)/2 + t;
Uo = (U-u)/2 + u;
sigma_1 = (To-t)/3;
sigma_2 = (Uo-u)/3;
F = @(T_user,U_user)(1./(2.*pi.*sigma_1.*sigma_2)).*exp(-
.5.*[((T_user-To).^2)/sigma_1.^2 + ((U_user-
Uo).^2)/sigma_2.^2]);
repeat=1;
while repeat
T_user = input ('Enter t:');
U_user = input ('Enter u:');
Q = dblquad(F,t,T_user,U_user,U)
repeat = input ('Do you want another calc? 1=yes 0=no');
end
end
```

Mat lab code for plotting the 3d curve of tripping probability of sensitive devices.

```
function probab(t,T,u,U)
To = (T-t)/2 + t;
Uo = (U-u)/2 + u;
sigma_1 = (To-t)/3;
sigma_2 = (Uo-u)/3;
F = @(T_user,U_user)(1./(2.*pi.*sigma_1.*sigma_2)).*exp(-
.5.*[((T_user-To).^2)/sigma_1.^2 + ((U_user-
Uo).^2)/sigma_2.^2]);
N = 10;
Q = zeros(N, N);
t_res = (T-t) / N;
u_res = (U-u) / N;
t_indx = 0;
for t_val = t:t_res:T
    t_indx = t_indx + 1
    u_indx = 0;
    for u_val = U:-u_res:u
        u_indx = u_indx + 1;
        t_val
        u_val
        Q(t_indx, u_indx) = dblquad(F, t, t_val, u_val, U);
        Q(t_indx, u_indx)
    end
end
 surf(t:t_res:T, U:-u_res:u, Q)
end
```