Optimal Selection of Voltage Sag Mitigation Solution Based on Event Tree Method

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***Abstract*—Modern commercial operations consist of critical equipments that are more susceptible to voltage sag events. The consistent and smooth running of these operations is often disrupted by voltage sags. Diverse range of solutions exist which can enhance the ride through capability of sensitive devices. This paper presents various voltage dip mitigation solutions and a methodology for analyzing the effectiveness and practical viability of these solutions. The proposed approach is based on event tree method which gives an indication about the extent of process interruption in the event of voltage sags. A case study is conducted in the paper with different combinations of practical mitigation solutions against voltage sags, in order to illustrate the applicability of the proposed approach.**

***Index Terms*—Event Tree, Power Quality, Power Conditioner, Voltage Sags.**

I. Introduction

POWER electronic and electronic equipments have turned out to be more sensitive to quality of electric power than their equivalent equipments developed a few decades ago [1]. Due to this increased sensitivity of equipments, electric utilities and customers have become more concerned about the quality of the electric power service. Comparing various power quality disturbances, e.g., voltage sags, voltage swells, interruptions, transients, voltage unbalance, voltage flickers and harmonics, the most frequent are voltage sags [2].

Majority of the modern industrial processes consists of critical devices like adjustable speed drives (ASD), personal computers (PC), programmable logic controllers (PLC), semiconductor devices (SD) and contactors that are highly sensitive to voltage sags [3]. The combination of sensitive equipments and voltage dips may result in high financial losses. Although power utilities strive hard to minimize the voltage sags in the network. However voltage sag performance of the power system cannot be guaranteed at all times. In order to reduce the susceptibility of sensitive devices to voltage sags, various power conditioning equipments are employed at customer's end.

The main focus of this paper is to utilize the concept of event tree methodology. Since calculation of financial losses of the customer due to voltage sags is well established by the methodology developed by the authors [4], this paper incorporates the same methodology with economical estimation methods to deduce the best possible voltage sag mitigation solution.

The publication is divided into sections. In Section II, various mitigation solutions that can provide some levels of protection for sensitive equipments against voltage sag events and economic measures that can help in selecting the economically feasible solutions are explained. The proposed assessment method is explained in Section III. In Section IV, the practicality of proposed approach is presented in a case study. Finally, a conclusion is drawn in Section V.

II. Optimal Selection of Mitigation Solutions

A. Voltage Sag Mitigation Solutions

Nowadays, various voltage sag mitigation solutions exist which can protect the sensitive equipments against voltage sag events. As shown in Fig. 1, there are four levels for implementing voltage sag mitigation solutions [5]. The optimal type, number and location of voltage sag mitigation solutions are determined based on the economical realization, vulnerability and importance of the customer operations. In the following subsections, the general characteristics of major technologies available for implementing voltage sag mitigation solutions for levels 1 to 3 are briefly discussed. Alternatives for level 4, utility solutions, are out of the scope of this paper.

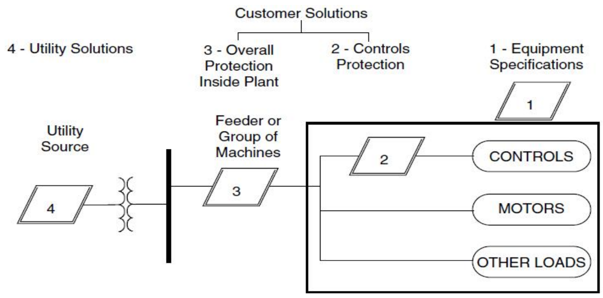

Fig. 1. Possible levels for employing voltage sag mitigation solutions [5].

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. The transfer time from supply to dip proofing status is less than 700 micro seconds [6]. The DPI can continue to supply voltage for about one to three seconds [7].

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Coil Hold-In Device (CHD): This device is the equipment level solution and falls into the category of devices meant for mitigating the effect of voltage sags on individual contactors and relays. This device can correct voltage sag events with the remaining voltage up to 25% of the nominal voltage [8].

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. Commercial available boost converter can help ASD to withstand against voltage sag events with the remaining voltage up to 50% of the nominal voltage for up to 2 seconds [9].

Uninterruptable Power Supply (UPS): This device is almost the equipment level solution but it can also be used as the plant level or the utility level solution too. For the safe continuous operation of the process, the transfer time from ac supply to battery should not be greater than 4 ms [5]. Sensitive equipments are not affected by the voltage sag if there is a high speed transferring (<1 cycle) from utility power to battery [7].

Dynamic Voltage Restore (DVR): This device can be used as the plant level or the utility level solution. It can provide protection only against voltage sags with the remaining voltage up to 50% of the nominal voltage [7].

B. 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". They are defined as follows:

Benefit-Cost Ratio (BCR): This economic measure gives the economic feasibility of the implemented voltage sag mitigation solution. The benefit-cost ratio is calculated by the following equations:

$$BCR = \frac{ACS \times PWF \times SLT}{SIC + \left(SOC \times PWF \times SLT\right)} \tag{1}$$

$$PWF = \sum_{t=1}^{SLT} \left(1 + p/100\right)^{-t} \tag{2}$$

where:

ACS	Annual cost saved corresponding to the savings accumulated per year after employing the solution
PWF	Present worth factor
p	Annual interest rate, in percent
t	Time period, in years
SOC	Annual operating cost of the implemented solution
SIC	Investment cost of the implemented solution
SLT	Life time of the implemented solution

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 the implemented voltage sag mitigation solution is calculated as follows:

$$PP = \frac{SIC \times 12}{(ACS - SOC)} \tag{3}$$

III. The Proposed Approach

A. General Concepts

Susceptibility of the sensitive equipments against voltage sag events is defined by voltage tolerance capabilities of these equipments. A variety of power conditioning instruments are often employed to improve the voltage tolerance capability, thereby increasing the ride through capability of its equipments against voltage sag events. This paper presents an assessment method to select the most economical mitigation solution from a variety of power conditioning equipments in order to improve the performance of sensitive devices to voltage dips involved in commercial operation.

The proposed method first utilizes the concept of finding the financial losses incurred on a customer operation described in publication [4]. It then integrates different technologies which can enhance the voltage tolerance curve and thus the performance of the devices against voltage sags. The financial losses are re-calculated after applying the mitigation solutions. The economic measures are evaluated for each solution by considering the costs incurred in applying the solution and potential benefit gained. The best possible solution in terms of practical applicability and economics are evaluated by comparing various solutions.

B. Evaluation Procedures

The evaluation procedure described in Section 5.2 of [4] can also be used for optimal selection of voltage sag mitigation solutions. The following steps 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 5.2 of [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 operational failure probabilities 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 5.2 of paper [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 (1) to (3), the benefit-cost ratio and payback period are calculated for the 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.

IV. CASE STUDY

For simplicity of the calculations, practicality of the proposed approach, for selecting best possible mitigation solution against voltage sag events on customer operations, is shown here by means of a semiconductor facility having momentary interruption cost of approximately $1,400,000 having a peak load of 30 MW and service voltage of 161 kV [7]. The financial losses due to voltage dips on specific operations of this facility which are estimated to have load of 500 kW have already been calculated in thesis [4]. The mitigation solutions are assumed to be applied on the same operations.

Economic data of typical voltage sag mitigation solutions have been provided in Table I. 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 all the targeted customer operations. A ten percent interest rate and 10 years of life time are assumed for the calculations.

TABLE I
ECONOMIC DATA OF TYPICAL VOLTAGE SAG MITIGATION OPTIONS [5] – [10]

Mitigation Option	Investment Cost (€/KVA)	Operating Cost (Percent of investment cost)	Threshold Voltage (Percent of remaining Voltage)
DPI	1960	–	–
BC	100	–	50
CHD	128 per device	–	25
UPS	377	25	–
DVR	188.5	5	50

A. Comparative Analysis

The benefit-cost ratio and payback period have been calculated for various voltage sag mitigation options using the methodology described in Section III. The results are shown in Figs. 2 to 6.

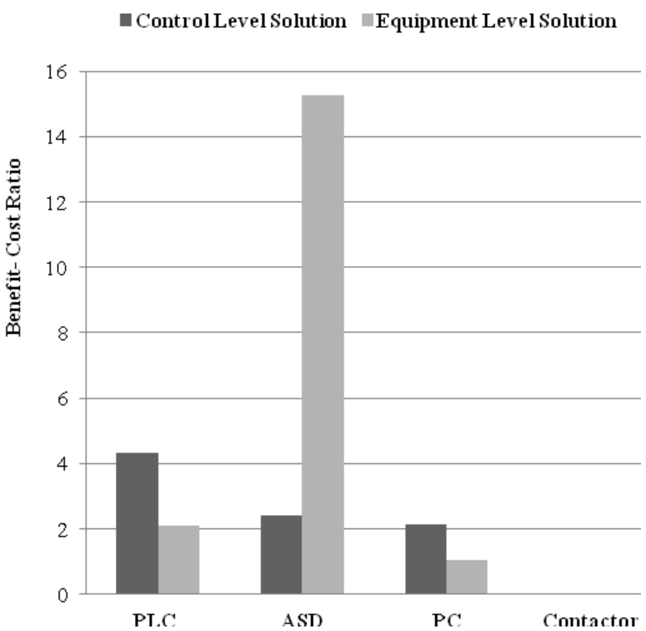

Fig. 2. Benefit-cost ratio when protecting one sensitive equipment.

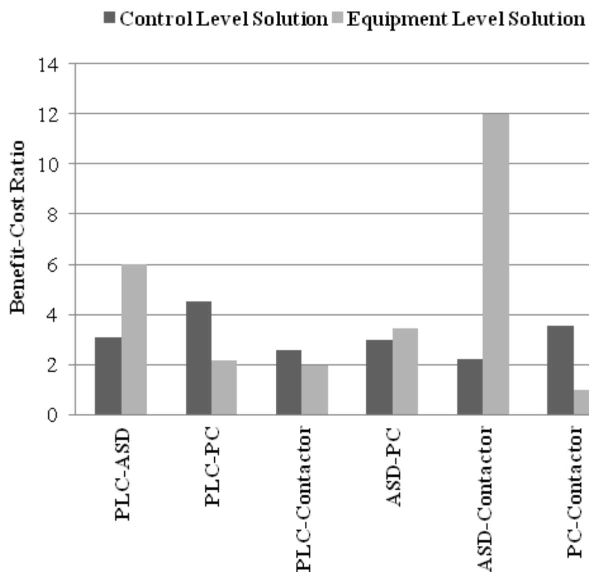

Fig. 3. Benefit-cost ratio when protecting two sensitive equipments.

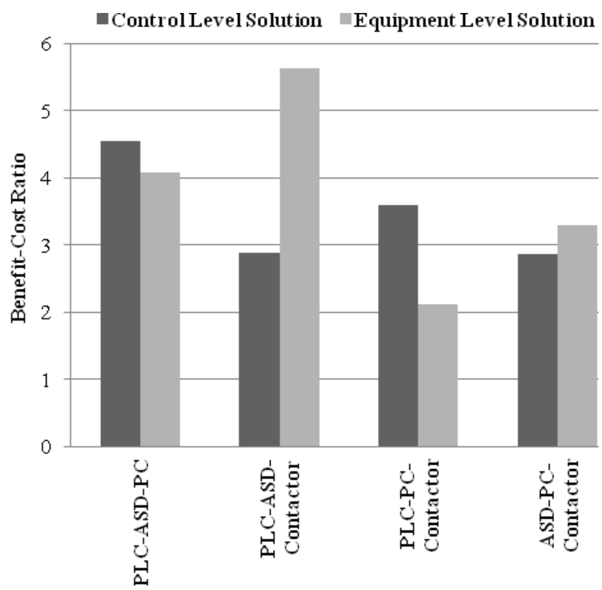

Fig. 4. Benefit-cost ratio when protecting three sensitive equipments.

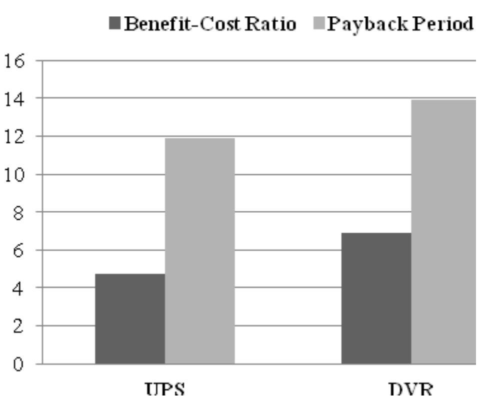

Fig. 5. Benefit-cost ratio and pay back period for plant level solutions.

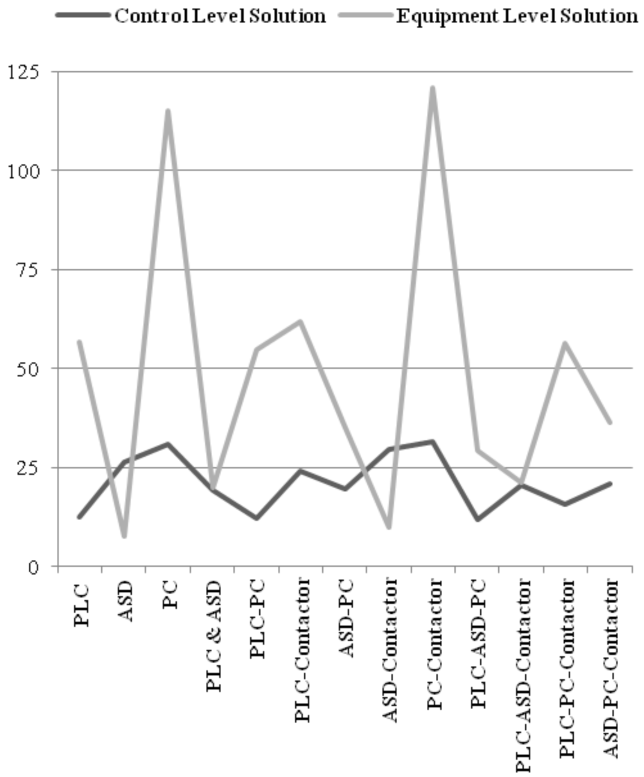

Fig. 6. Pay back period for various mitigation options.

The cost of the 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. These solutions normally require regular testing and maintenance activities. In few cases, the equipment level solutions can be economical as well. The main drawback of these solutions 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 [7]. The plant level solutions are also economically viable. But they usually require much higher investments. 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.

B. Sensitivity Analysis

There is a diverse range of downtime costs among different customers and hence the cost of momentary interruptions varies significantly. This cost mainly depends on the nature of the customer operations and sensitivity of its equipments. For example, the amount of costs can vary from high values such as $54000 per megawatt for a semiconductor industry to small values such as $2000 per megawatt for a plastic extrusion, pulp and paper processes [7]. To find the impacts of the momentary interruption cost on the selection of mitigation solutions, the calculations have been repeated for semiconductor industry and plastic extrusion pulp and paper industry with the above mentioned momentary interruption costs. The results are shown in Figs. 7 and 8. As it can be seen from the results presented in these figures, the

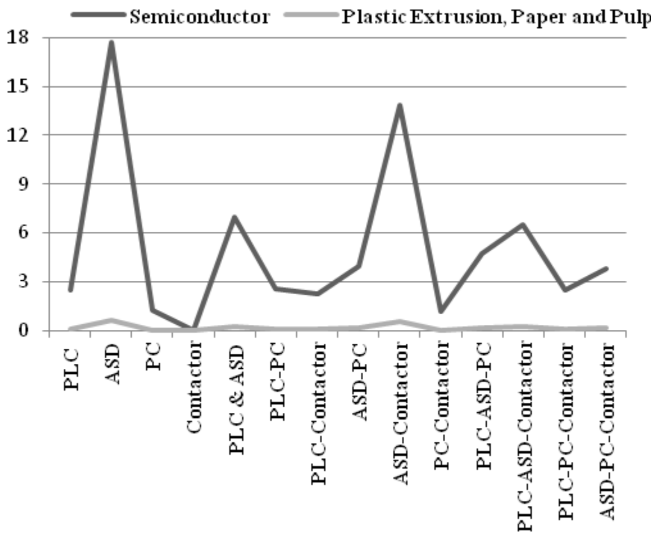

Fig. 7. Benefit-cost ratio when employing equipment level mitigation solutions for semiconductor and plastic extrusion, paper and pulp industries.

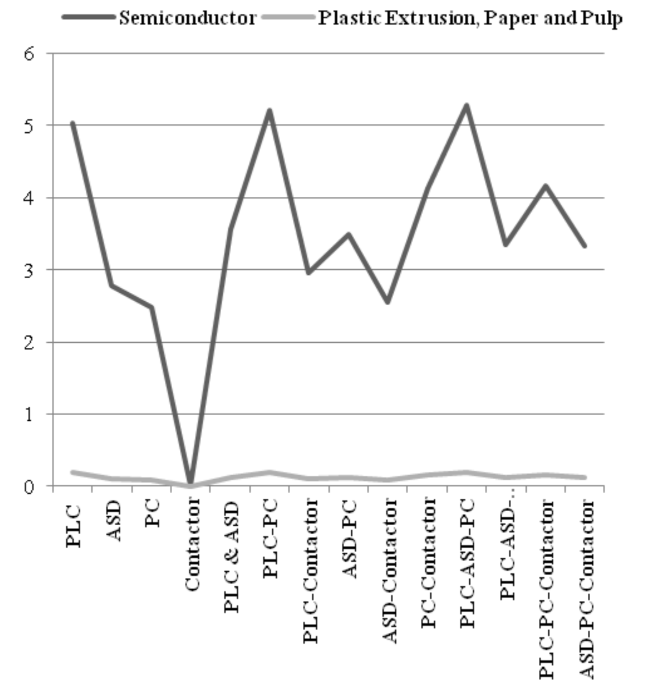

Fig. 8. Benefit-cost ratio when employing control level mitigation solutions for semiconductor and plastic extrusion, paper and pulp industries.

mitigation solutions are feasible only for an industry which has a high momentary interruption cost.

V. Conclusion

This paper presented various voltage dips mitigation solutions for most sensitive industrial equipments and proposed methodology for assessing the applicability of different voltage sag mitigation options from cost-effectiveness point of view. The proposed method was based on event tree methodology. It takes into account all the possible malfunctioning states of the industrial operation. The proposed methodology is simple, comprehensive and adaptable for various consumer operations.

A case study is presented in which the proposed method is applied on a semiconductor industry for presenting the practical demonstration of the proposed technique. Diverse voltage sag mitigation solutions were examined to find the most potential mitigation solution for this facility. The feasibility of different mitigation solutions were shown as a function of the momentary interruption cost in the sensitivity analysis. As presented by the paper, the calculations show that there is a high cost difference of mitigation solution for different industries. 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.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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