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A critical review on the methods for calculating the risk of process failure because of voltage sags

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***Abstract*—Because of inherent stochasticity, cost implication of voltage sags compared to scheduled outages are very high typically for an industrial or commercial load. Since, different types of equipment behave differently during voltage sag events, and interconnection of these types of equipment to control a process or a load is very complex, exact cost calculation of voltage sag events is difficult. The favorable or skeptical ways of cost calculation may not indicate the actual risk of process failure, which is essential for performing the cost-benefit analysis to evaluate possible mitigation solutions. Therefore, calculation of "risk of process failure" under voltage sag events assumes significance. This paper critically reviews the concept of "risk of process failure" as viewed by different researchers and highlights the necessity of further research in this area. The overall risk of process failure can be useful for cost-benefit analysis of mitigation methods to minimize the cost implication of voltage sags.**

Keywords*—*Cost-benefit analysis, equipment sensitivity, faults, power quality (PQ), risk of process failure, voltage sags

I. INTRODUCTION

AMONGST all Power Quality (PQ) events, most of the high-tech industries are susceptible to short interruptions followed by voltage sags, voltage swell, and harmonics [1]. The cost of unscheduled interruption is much higher compared to scheduled interruption. However, the total number of customers affected because of voltage sag events are the highest. And also, impact of voltage sag event is different for different types of customers. Therefore, *"economics of voltage sags"* is relatively more important amongst all PQ issues.

Estimating financial consequences of a PQ event is a difficult task and not many practical studies are carried out till date [2]. However, the cost of financial losses due to PQ events is significant, and hence, the customers are keen to improve PQ at their connection point (POC) [3, 4]. It is very expensive as well as difficult to eliminate voltage sags completely from the network; and therefore, none of the stakeholders, either utility or customer, alone would like to invest for the mitigation solutions [4].

Although, voltage sag or dip events in an electricity network may occur because of several reasons, such as, (i) sags at a POC or inside a consumers' premises, (ii) motor starting in a neighbouring installation, (iii) fault in the local network, (iv) fault in the neighbouring network, (v) fault in the upstream network, (vi) saturation of distribution transformers, (vii) delay in operation of protection devices, (viii) switching of capacitor banks, (ix) connection of large load into the network etc. Total damage incurred by industrial and commercial customers because of voltage sag events is the highest. It has been observed that sag events because of fault in the local network are the main reason of industrial process failure, and needs to be examined thoroughly. Fault events in the electricity network are stochastic in nature, and their impact on the customers are also stochastic. According to the IEEE standard [5], a voltage sag event may be defined as *the decrease in root mean square (RMS) value of voltage within 0.1 pu and 0.9 pu for a duration of more than 0.5 cycles to 1 minute. While supply voltage* ≤ 0.1 *pu is considered as short interruption and* ≥ 0.9 *pu is considered as normal voltage variation.* Voltage variation for a duration of fewer than 0.5 cycles is called momentary interruption. According to IEC standard 1000 [6], a voltage sag refers to *a sudden reduction of voltage at a point in the electrical system, followed by a voltage recovery after a short period of time, from 0.5 cycles to a few seconds.*

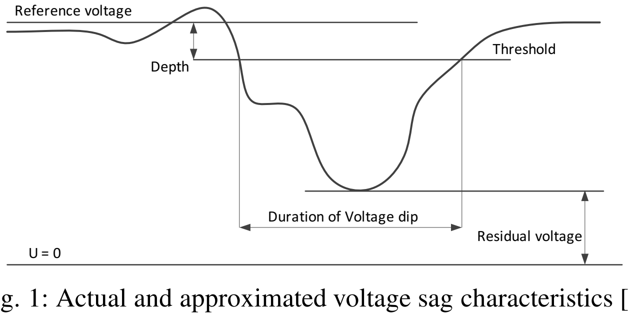

Fig. 1: Actual and approximated voltage sag characteristics [7]

The "severity" of a voltage sag event is expressed by voltage and duration of sags at a "point of observation". For representation, the sag characteristic curve is approximated to be rectangular. However, as shown in Fig. 1, since network impedance does not remain constant during a voltage sag event, fault duration characteristics is not rectangular in shape [7]. Voltage sag event is mainly characterized by a threshold voltage, a residual voltage, and duration of the sag event. Post-fault sag condition is not usually studied, as the number of dependent voltage sag events are negligible [8].

The cost of voltage sags depends on the cost of interrupted processes. In the absence of exact expression of the cost of voltage sags, indirect cost analysis is used. However, several survey analysis shows, there is a huge gap between customer's estimate of the cost of sag events and their willingness to invest in sag mitigation devices [4, 9]. Therefore, a detailed evaluation of the cost of voltage sags using the available data is very much essential.

II. A DISCUSSION ON STOCHASTIC EVALUATION OF COST OF VOLTAGE SAGS

PQ monitoring program requires long monitoring period and is therefore, costly. Hence, the frequency of occurrence of sag events is stochastically measured. The occurrence of different sag events can be obtained from *site-specific historical data*. For example, in high impedance earthed MV distribution network, only 3-phase short circuit on the MV side causes significant voltage sags on the LV side [4]. In case of an unbalanced fault, depending on the connection of transformers and processes, phase to neutral or phase to phase voltage need to be examined for sag calculations. Sometimes, earth faults on the LV side can be neglected if MV side is not grounded (as in Finnish system) [4, 10].

Mean time between failure (MTBF) determines the susceptibility of cables, overhead lines, and line terminals to failure. The inverse of MTBF is called the fault rate; which is used for determining stochastic dip frequency estimation. Occurrence of different types of faults, such as balanced, or unbalanced can be represented using a probability distribution function. While doing the fault analysis, the primary protection is assumed to be 100% reliable [11]. The delay in the operation of protection devices, availability of secondary protection equipment, selected voltage threshold, and location of these protection devices determine the duration of voltage sags [12]. Classically, use of a fault impedance, $Z_F = 0\ \Omega$, generates a pessimistic estimate of sag frequency [4]. However, since fault impedance can vary over a wide range, it is useful to consider a probability distribution of the fault impedance [13].

Either of fault position, critical distance, and Monte-Carlo methods is used for stochastic evaluation of the frequency of voltage sags in a network [14]. Calculation of sag frequency using fault position method depends on the calculation of network residual voltage, at different fault positions uniformly spread across the network. For better accuracy of voltage sag frequency, a large number of fault positions uniformly spread across the network are required to be evaluated. In comparison to fault position method, critical distance method calculates the exposed sag sensitive area of the network around a sensitive customer. Monte Carlo method uses probability density function associated with each of the variables (such as, fault position, fault impedance etc.). Expected sag frequency is obtained after large number of iterations.

An economic loss because of sag event very much depends on the physical connectivity of loads within an installation. In case of a balanced load and an unbalanced fault, calculation of exact sag characteristic is different [11]. Fig. 2 shows an example for calculation of residual voltage and sag duration in case of an unbalanced fault experienced by a balanced load. Residual voltage and the sag duration can be determined from the grayed out region in Fig. 2.

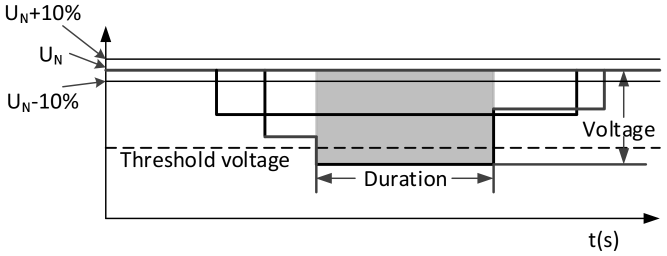

Fig. 2: Equivalent 3-phase voltage dip for an unbalanced fault [7]

Industrial or commercial processes are majorly controlled by series-parallel combinations of various dip sensitive equipment. The difference between a sensitive and a non-sensitive equipment is, a non-sensitive equipment trips when the residual voltage falls below a certain threshold, however, a sensitive equipment may trip depending on its immunity characteristic. Recent studies show that, every 'sensitive' equipment has three regions of operation: (I) no trip (where, the equipment will not trip), (II) trip (where, the equipment will trip), (III) area of uncertainty (where, the equipment may or may not trip depending on sag parameters) [15]. Voltage-duration immunity characteristic of a typical sensitive equipment is shown in Fig. 3.

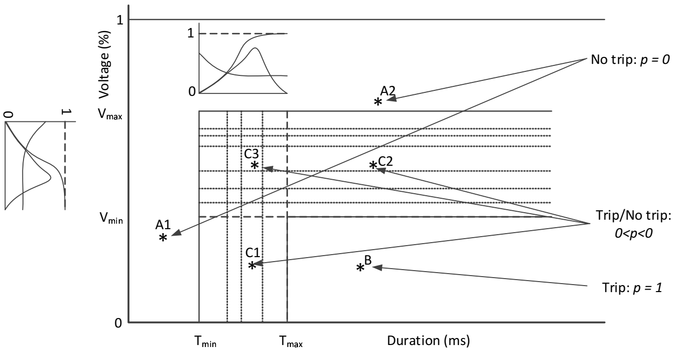

Fig. 3: Expected behavior of typical sensitive equipment against voltage sags [15]

Typical automation equipment, such as, programmable logic controller, adjustable speed drive, personal computer, contactor switches etc., are sensitive to voltage sags. To reduce the impact of supply voltage dip at the POC, various contributing factors, such as, customer type, size and their location in the network, must be envisaged [16]. Sensitive equipment can be vulnerable to, (i) voltage magnitude only (process controls, motor drive control, and semiconductor manufacturing equipment), (ii) both magnitude and sag duration (all equipment with switched mode power supply) and (iii) other than above two conditions (e.g., contractors are affected by point-on-wave at which sag is initiated) [17].

III. METHODS FOR CALCULATION OF RISK OF PROCESS FAILURE

Customers will incur an economical loss when a part/whole process gets disrupted because of voltage sags. Difference between calculation of cost of permanent interruptions and voltage sags is, during permanent interruption, there is a complete shut-down of all processes, hence, failure of individual sub-processes need not be considered. However, in case of voltage sags, depending upon the sensitivity of equipment constituting a sub-process, all the equipment may not fail. There exist three factors for disruption of a process [18]: (i) equipment's immunity towards voltage sags, (ii) interconnection of sub-processes, and (iii) severity of voltage sag events. Use of cost of permanent failure to estimate the cost of voltage sags will generate a pessimistic estimation, and hence for the cost-benefit analysis of different mitigation solutions, exact calculation of the cost of voltage sags is very much essential.

Independent of methodologies used for calculation of voltage sag events reported in the literature, the financial loss because of process failure is calculated as,

$$\begin{matrix}\text{Financial}\\\text{loss}\end{matrix} = \sum_{\forall\ sag\ events} \begin{matrix}\text{Risk of}\\\text{process failure}\end{matrix} \times \begin{matrix}\text{Cost of each}\\\text{Disturbance}\end{matrix}$$

Over the course of time, different methods for calculation of financial loss because of sag events are evolving. However, these different procedures can be divided into two categories, (i) calculation of the risk involved for process failure, and (ii) calculation of the cost of each disturbance. Since all major processes are driven by various combination of sensitive equipment, the risk of process failure and cost of each disturbance are a complex function of the composition of sensitive equipment and their participation to constitute the whole process. Both of these categories are independently developing. Since total cost of voltage sags is dependent on the connection of sensitive equipment constituting a sub-process, various assumptions are made in this regard to accurately calculate the cost of voltage sags. In this paper, the focus has been laid on an estimation of "risk of process failure because of voltage sag events", and for consistency, these methods have been presented in this paper in a time sequential order with respect to the publication year.

A. Cost-benefit evaluation of voltage conditioners installation in industrial and commercial power systems (2003) [16]

Processes in a network can be interconnected for successful operation of a plant. Depending on the availability of storehouse in all of the processes, immediate shut-down of processes because of failure of other processes may not be essential. Similarly, disruption of any process can affect other processes too. In this regard, processes are required to be divided into different shut-down categories, where, disruption of one of the processes from one of the shut-down category will disrupt all other processes of that category.

Likewise, if a process constitutes of multiple sensitive types of equipment, so that, failure of one of these types of equipment will disrupt the whole process. These types of equipment are said to be "logically connected in series". The overall immunity of the process is based on the union of the voltage tolerance curves of its equipment. This method is called as 'process wrapping' method.

The method discussed in this paper is applied to processes controlled by non-stochastic sensitive equipment. Given, the immunity characteristics of these different kinds of sensitive equipment and processes of a similar shut-down category, a compound immunity curve can be found using process wrapping method. Because of non-stochastic nature of equipment's immunity curve, reliability improvement with parallel connected equipment is not considered. Although, this method does not consider stochastic nature of processes of different shut-down categories, stochastic nature of the processes can be appropriately incorporated.

B. Introducing prob-a-sag - a probabilistic method for voltage sag management (2004) [19]

In this method, sag sensitivity or tripping probability (D) of different equipment controlling a process are used for calculating overall process sensitivity. The sag sensitivity matrix is a function of two independent variables, residual voltage, and sag duration. Various equipment can be connected in series parallel combination to control a process. For example, a process may consist of series connected q number of equipment, and in each group, r_k number of equipment connected in parallel for redundancy. In this regard, overall process sensitivity P will be calculated as:

$$P = 1 - \left[\prod_{k=1}^{q} \left[1 - \prod_{k=1}^{r_k} D \right] \right] \tag{1}$$

This is a pioneering method that uses complex stochastic nature of tripping probability to calculate the immunity characteristic of processes, and hence, this method is also called as 'Prob-a-Sag' method. However, relative connection of processes to constitute overall plant output and associated probabilities are not discussed in this paper.

C. The influence of process equipment composition on financial losses due to voltage sags (2004) [11]

A load, which is controlled by various sensitive equipment does not remain constant throughout the day. And, tripping of a sensitive equipment symbolizes the failure of a part of the process. The method described in this paper assumes a non-stochastic, rectangular immunity curve. Expected risk of a voltage sag event can be calculated in this method considering various load composition and their probability of occurrence. The authors have ignored various equipment and process connectivity to calculate an overall risk. Partial failure of processes is also not accounted. This paper does not look into component-level details. Therefore, the total cost of process failure calculated using this method requires further validation.

D. Estimating economic impact of voltage sags (2004) [20]

In the presence of multiple sag sensitive equipment, failure modes of each of the processes are required to be considered individually; and a failure probability chart is prepared (see Fig. 4) based on a cause-effect relationship between equipment failure and process failure.

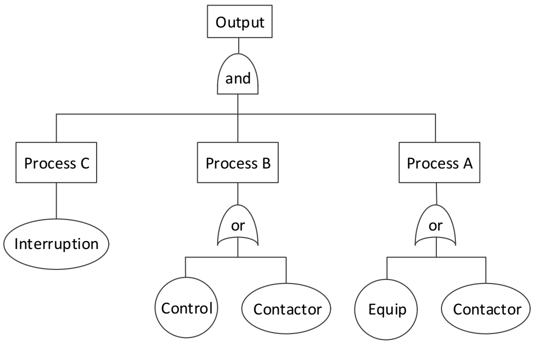

Fig. 4: Example of a Graphical Tree [20]

Fig. 4 depicts that the process C is least sensitive while process B fails if either control or contactor switch fails, and process A fails in case of equipment or contactor switch failure. Also, the process plant will shut down, if all three process fails. These failure modes are mutually exclusive and exhaustive. This paper does not consider the probabilistic nature of equipment immunity characteristics; however, it can be suitably incorporated.

E. Probabilistic assessment of financial losses due to interruptions and voltage sags (2006) [15]

Since several sensitive equipment has non-rectangular voltage-tolerance characteristics, these process controlling equipment are required to be categorized. The failure probability of these processes can be obtained from various sources, such as, the equipment manufacturers, available standards, or through laboratory tests. The method described in this paper also considers stochastic nature of process failure. As an extension to the method discussed in [19], equipment immunity characteristic curve has been considered as a function of univariate random variables, residual voltage at the POC (‘V’), and duration of sag event (‘T’) respectively.

Typical sag immunity curve has been shown in Fig. 3. It can be noted that the sag sensitivity characteristics can also be non-rectangular in nature. Sag sensitivity curve can also be a function of other parameters of voltage sags, such as, the point-on-wave at which the voltage sag had initiated. Assuming statistical independence of residual voltage and duration, Bayes’ rule can be applied to calculate the total probability of failure in region C ($p_{XY}(T,V)$). The probability of failure or the risk of process failure because of voltage sags can be expressed by, multiplication of these probability distributions.

$$p_{XY}(T,V) = p_X(T)p_Y(V); T_{min} \leq T \leq T_{max}, V_{min} \leq V \leq V_{max} \tag{2}$$

Where, $p_X(T)$, and $p_Y(V)$ are probability density functions. Likewise in [19], an overall probability of process trip can be calculated, assuming equipment can be connected series-parallel combination to complete a process. This method also does not consider how different processes are interconnected to calculate total risk of plant disruption.

F. Economic assessment of voltage sags based on quality engineering theory (2007) [21]

When voltage magnitude or duration of voltage variation during sag events deviates from the quality standard, there will be an economic loss associated with this deviation. In this problem, inverse normal load function (INLF) along with the signal to noise ratio (SNR) concept has been used to measure the total risk of voltage dip. As depicted in this method, expression for monitory loss for deviation from voltage quality standard is given by:

$$L_i(x) = K_i \left\{ 1 - exp\left(-\frac{(x-T)^2}{2\sigma_i^2} \right) \right\} \tag{3}$$

Where, σ_i^2 and K_i are, process sensitivity parameter and maximum loss value respectively and are calculated from the historical data. Index ‘i’ represent different duration of voltage sag events. x is the sag voltage and T is the target performance. Different types of voltage sag events can be linearly combined, using the weights calculated from SNR concept.

Therefore, the risk of a process failure is proportional to voltage deviation from a quality standard. However, process or equipment level details are not considered in this method.

G. Economic loss assessment of voltage sags (2010) [18]

Given rectangular immunity curves of various sensitive equipment (as shown in Fig. 3), this paper approximates, the process tripping probability can be calculated by averaging out immunity characteristics of constituting equipment. For example, if the sensitivity curve of a particular equipment, ‘i’ is defined by $\{V_{i,max}, V_{i,min}, T_{i,max}, T_{i,min}\}$, then, overall sensitivity curve of different equipment can be linearly combined as, $V_{max} = \sum_i \alpha_i V_{i,max}$, $V_{min} = \sum_i \alpha_i V_{i,min}$, $T_{max} = \sum_i \alpha_i T_{i,max}$, $T_{min} = \sum_i \alpha_i T_{i,min}$. ‘$\alpha_i$’ are suitably selected. Failure probability of the process in the tripping region are proportional to deviation in voltage and duration from the “quality standard”. Overall process failure probability of the plant can be defined as,

$$P_{i,j} = \frac{(V_{max} - V)(T - T_{min})}{(V_{max} - V_{min})(T_{max} - T_{min})} \tag{4}$$

However, validation of the existence of such linear approximation of immunity curves is not justified in this paper.

H. Risk-Based Assessment of Financial Losses Due to Voltage Sag (2011) [22]

Total electricity consumption in a plant represents the intensity of that process plant. For example, in an industry, process activity is maximum during peak hours; and therefore, the cost of process failures are also very high during those hours. Given a seasonal variation of the industrial production, the electricity requirement of the plant also varies. Therefore, electricity demand can represent risk of voltage sag events.

Since process composition in a plant varies throughout a day, the method as described in [20] has been used to independently calculate the probability of failure at the different point of the day. Total plant risk throughout the day has been calculated by considering the probability of different process composition. This paper considers process level failure probability and composition of different processes, to calculate overall plant failure probability. However, equipment level details are also not considered in this paper.

I. Optimal selection of voltage sag mitigation solution based on event tree method (2012) [23]

When more than one process control equipment is present, a *step-by-step* equipment composition of various sub-processes is required to be considered for calculating overall risk of a process using that equipment. Therefore, in this paper, an "event tree" has been developed based on the logical order in which these types of sensitive equipment are connected.

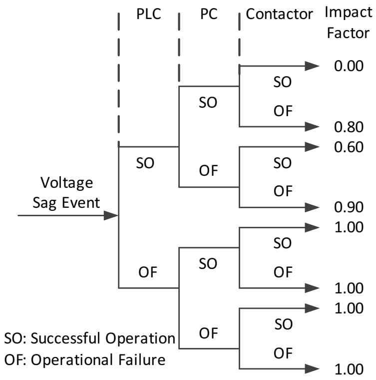

Fig. 5: Event tree diagram for a typical process [23]

A typical process tree is shown in Fig. 5. 'Impact factor' of an event, as shown in the figure, represents the financial impact of failure of an equipment, compared to complete process interruption for a given voltage sag event.

This method addresses the majority of the disadvantages of other methods proposed in the literature. However, presence of upstream or downstream processes, or availability of storehouse for calculating risk of a process failure is not taken into account in this paper.

IV. DISCUSSION

Sensitive equipment is an integral part of a process, and therefore, for reducing the process sensitivity towards voltage sags, the arrangement of these sensitive equipment can not be modified. However, if sag-duration characteristic itself is modified, processes will become less sensitive to the voltage sag event. Reduction in sensitivity of these types of equipment can be achieved by sag mitigation devices, such as automatic voltage regulator (AVR), dynamic voltage restorer (DVR) etc. However, if and only if, reduction in the cost of a process failure is higher than investment cost of these mitigation devices, investment on this mitigation devices will be worthy, and risk of process failure will be minimized.

'Cost of sag events' and 'risk of process failure', both are a complex function of sensitive equipment composition and their sensitivity characteristics. Therefore in this paper, the problem "given a voltage sag characteristic at the POC, what is the probability of failure of processes, which is consisting of various sensitive equipment?" as addressed in various literature are discussed. Assuming, the probability of occurrence of a sag event is uniform throughout the day, the risk of losing at least one process is higher compared to the probability of failure of at least one process when the number of processes running at a time is less. Equipment driving a process plant can not be modified. But, processes can be suitably executed throughout the day, so that, by distributing these processes probability of process failure is reduced.

Overall, the failure modes of a process because of voltage sags are dependent on several factors, such as, (i) inter-connection of sensitive equipment to constitute a sub-process, (ii) availability of upstream/downstream storage houses, (iii) successful operation of upstream/downstream processes, (iv) inter-connection of sub-process to constitute a process, and (v) modeling of process sensitivity characteristics. In addition, the cost of voltage sags also depends on, (vi) cost of each process failure, (vii) process running at different instants in a day.

Most of the methods that have been discussed in this paper uses the concept, "a process is made up of different sag sensitive equipment" up to a certain degree. However, depending on the use of equipment sensitivity characteristics, calculation methodology for calculation of risk of process failure can be divided into three categories: (i) methods that considers sensitivity characteristics to be non-probabilistic, (ii) methods that considers sensitivity characteristics to be probabilistic, and (iii) methods that do not use equipment sensitivity characteristics. Equipment sensitivity characteristics can be non-probabilistic, and rectangular in nature. In this regard, authors of [16] have proposed a process wrapping curve; where disruption of one equipment in a set of equipment disrupts the whole process. In [11], the authors have considered that composition of these sensitive types of equipment can vary over a wide range, with a probability of occurrence of each of each kind of composition. Hence, expected the cost of process disruption calculated based on these probabilities will determine the risk of process failure. In [20], composition of various equipment to form sub-processes and constitution of sub-processes to constitute a whole process is depicted in a graphical tree. However, with the recognition that, process sensitivity characteristics to be probabilistic, use of non-probabilistic characteristics was gradually eliminated.

In [21], the authors did not consider 'a composition of sensitive equipment constituting a process'. The authors have developed a risk function, which calculates the anomaly of sag-duration characteristic from the normal operating condition. However, use of risk function for calculating the process failure cost requires further analysis.

Probabilistic nature of equipment sensitivity characteristics was first described in [19]. When different equipment are controlling a process, the probability of successful operation of the process depends on the series-parallel combination of these kinds of equipment. Subsequently in [15], it is shown that sensitivity curves depend on residual voltage and sag duration independently. Non-rectangular sensitivity curves of various equipment, and special cases, where, sensitivity curves is a function of other variable such as the point-on-wave at which the voltage sag had occurred are also presented in this paper. However, in [18], an equivalent probability distribution assuming a linear combination of rectangular sensitivity curves has been developed. In [22], process composition at different points the day for successful plant operation has been considered. However, equipment level probability details are not considered in this paper. In [23], the authors have presented a step-by-step equipment level composition method to calculate overall probability of failure.

Therefore from various literature, it can be observed that risk calculation of processes and plants depends on a series-parallel combination of various sensitive equipment. Complex probabilistic sensitivity characteristic was gradually adopted for calculation of risk of process failure. However with the adoption of complex nature of process immunity characteristic, computational difficulties are also increased. It is to be noted that, since all of this calculation are mandatory for the cost-benefit analysis of mitigation devices, use of a complex model of these processes may pose computational difficulties.

As suggested by [23], a step-by-step identification of various equipment and their connection in a sub-process is very much essential to measure the overall impact of risk of failure of processes. However, in a big industry, loads/processes at a different point in time are different. Depending on the selected industry, load variation can be stochastic/non-stochastic in nature. Therefore, to find out different sub-processes and their composition to constitute the whole process can be challenging. From the modeling point of view, as it was considered in [16] that the status of upstream/downstream processes and availability of storehouse are to be considered to calculate overall risk of plant failure. In conclusion, further investigation for accurate modeling of the sensitive equipment controlling the process is very much essential.

V. CONCLUSION

This paper presents a comparative analysis for calculation of risk of process failure because of voltage sags. The risk of process failure as determined in these methods will help in the calculation of the cost of voltage sag events. It is also found from the literature that, the failure probability of a process not only depends on its own failure rate; but the failure rate of other processes associated with that plant, availability of storage house, etc. An availability of a model that encompasses all the modeling aspects presented in the published literature will result in close to the accurate cost of voltage sag event. However, exact cost calculation of risk of process failure requires a detailed model of equipment and processes in a plant. In addition, a trade off between computational complexity and solution accuracy is essential to meet the customized needs of various customers.

REFERENCES

[1] S. A. Yin, C. L. Su, and R. F. Chang, "Assessment of power quality cost for high-tech industry, in *IEEE Power India Conf.*, New Delhi, India, 2006.

[2] S. Bhattacharyya, "Consequences of poor power quality for grid operators, in *20th Int. Conf. and Exhib. Electricity Distribution*, Prague, 2009.

[3] S. Bhattacharyya, J. F. G. Cobben, J. M. A. Myrzik, and W. L. Kling, "Decision Path for Investments on Solutions to Power Quality Problems, in *IEEE Benelux Young Researchers Symp. in Electrical Power Engineering,* Eindhoven, The Netherlands, Feb., 2008.

[4] P. Heine, P. Pohjanheimo, M. Lehtonen, and E. Lakervi, "A method for estimating the frequency and cost of voltage sags," *IEEE Trans. Power Syst.*, vol. 17, no. 2, pp. 290–296, May, 2002.

[5] "IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment," *IEEE Std 1346-1998*, 1998.

[6] "Description of the environment - electromagnetic environment for low frequency conducted disturbances and signalling in public low-voltage power supply systems," *IEC 1000-2-1*, 1990.

[7] A. Baggini, Handbook of Power Quality. *John Wiley & Sons*, Ltd., 2008.

[8] H. H. Schiesser and B. Heimbach, "Customer costs due to major voltage disturbances: Estimations for an urban distribution network in Switzerland, in *22nd Int. Conf. and Exhib. Electricity Distribution (CIRED 2013)*, Stockholm, 2013.

[9] S. Kfeolu and M. Lehtonen, "Interruption costs of service sector electricity customers, a hybrid approach," *Int. J Elec. Power Energy Syst.*, vol. 64, pp. 588 – 595, Jan. 2015.

[10] G. Celli, F. Pilo, G. Pisano, and G. G. Soma, "Stochastic assessment of voltage dips for a PQ oriented distribution system development," in *Int. Conf. Probabilistic Methods Applied to Power Systems, PMAPS*, Stockholm, 2006.

[11] C. P. Gupta, J. V. Milanovic, and M. T. Aung, "The influence of process equipment composition on financial losses due to voltage sags," in *11th Int. Conf. Harmonics and Quality of Power*, pp. 28–34, 2004.

[12] J. F. L. van Castern, J. F. G. Cobben, J. H. R. Enslin, W. T. J. Hulshorst, W. L. Kling, and M. D. Hamoen, "A customer oriented approach to the classification of voltage dips, in *18th Int. Conf. and Exhib. .Electricity Distribution (CIRED 2005)*, Turin, Italy, 2005.

[13] S. O. Faried and S. Aboreshaid, "Stochastic evaluation of voltage sags in series capacitor compensated radial distribution systems," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 744–750, July 2003.

[14] M. N. Moschakis and N. D. Hatziargyriou, "Analytical calculation and stochastic assessment of voltage sags," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1727–1734, July 2006.

[15] J. V. Milanovic and C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sags-part I: the methodology, *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 918–924, Apr. 2006.

[16] S. Quaia and F. Tosato, "Cost-benefit evaluation of voltage conditioners installation in industrial and commercial power systems," *Euro. Trans. Electr. Power*, vol. 8, pp. 423-428, 1998.

[17] M. McGranaghan and B. Roettger, "Economic Evaluation of Power Quality, in *IEEE Power Engg. Review*, vol. 22, no. 2, pp. 8–12, 2002.

[18] Z. Ding, Y. Zhu, and C. Chen, "Economic loss assessment of voltage sags, in *China Int. Conf. Electricity Distribution (CICED 2010)*, Nanjing, 2010.

[19] P. Pohjanheimo and M. Lehtonen, "Introducing prob-a-sag - a probabilistic method for voltage sag management, in *11th Int. Conf. .Harmonics and Quality of Power*, pp. 250–254, 2004.

[20] J. Wang, S. Chen, and T. T. Lie, "Estimating economic impact of voltage sags, in *2004 Int. Conf. Power System Technology (PowerCon 2004)*, pp. 21–24, Nov. 2004.

[21] G. Li, M. Zhou, B. Zhang, and J. Yang, "Economic Assessment of Voltage Sags Based on Quality Engineering Theory, in *IEEE Lausanne Power Tech. Conf.*, no. 617, pp. 1509–1514, Lausanne, 2007.

[22] J. Y. Chan, J. V. Milanovic, and A. Delahunty, "Risk-Based Assessment of Financial Losses Due to Voltage Sag," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 492–500, Apr. 2011.

[23] M. Yasir, S. Kazemi, M. Lehtonen and M. Fotuhi-Firuzabad, "Optimal selection of voltage sag mitigation solution based on event tree method, in *Electric Power Quality and Supply Reliability Conf. (PQ)*, pp. 119–124, Tartu, 2012.