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Assessment of Financial Losses Due to Voltage Sags Using Optimal Monitoring Schemes

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Abstract. The paper investigates the effectiveness of optimal placement of monitors in the assessment of financial losses due to voltage sags. Optimal sag monitoring schemes and typical power quality monitoring sites are used to perform a risk-based assessment of financial losses. The influence of the number and location of monitors on the outcome of a financial-loss analysis in voltage sag studies is also looked into. The results of the analysis are illustrated using a 295-bus generic distribution network (GDN) and considering a range of sensitive customers.

Key words

Financial loses, optimal monitor placement, voltage sag.

1. Introduction

The interest in power quality has increased enormously in recent years. There are several reasons for this increase including: the use of equipment more sensitive to voltage disturbances; industrial processes less tolerant to equipment failure; and competitive companies highly averse to the loss of production. These factors have lead to much higher financial losses. Of the several types of power quality disturbance that entail financial losses to businesses, voltage sags and short interruptions have been considered as the most damaging [1]. As an example a 2007 power quality report [2] indicates an annual loss of €86 billion in the EU due to voltage sags and short interruptions. Without doubt, financial losses are the current driving force for power quality analysis.

IEEE Standard 1346-1998 [3] states that the main aspects of the evaluation of financial losses at customer facilities due to voltage sags are: voltage sag performance at network and individual site levels, customer's equipment compatibility to voltage sags, and financial assessment of the losses incurred by process disruptive sags.

The sag performance of the network is the most important factor of voltage sag management since it represents the severity of the problem for the customer, and is the benchmark for power quality contractual terms [4].

Power quality monitoring provides the network operator with information about a wide range of power quality phenomena; including voltages, currents and power consumption, both for the entire system and for individual sites and customers. This information can be used to assess the economic losses incurred by voltage sags. Clearly, more accurate sag performance information can lead to more accurate assessment of the economic losses incurred by voltage sags. It is clear that entire system monitoring (at all nodes) is ideal, practical and economically possible in transmission systems. However complete system monitoring is not readily achievable in distribution systems with hundreds of substations and feeders, and thousands of end users at different voltage levels. For instance, the accuracy of sag performance estimation is dependent on the number and locations of power quality monitors. This is particularly true for non-monitored buses, where the sag performance is usually estimated by statistical predictions using measurement records from monitored buses or by network simulation with historical fault data.

From the array of existing optimal power quality monitor placement methods, those proposed in [5] and [6] are the most suitable for voltage sag monitoring, the latter being more robust and thus providing more accurate results. None of these methods however has been used to assess the financial losses entailed by voltage sags.

This paper aims to fill in this gap by carrying out an assessment of financial losses due to voltage sags employing optimal sag monitoring schemes determined with the method proposed in [6]. The influence of number and location of monitors in the accuracy of sag losses estimation will be analyzed. The studies will be performed in a generic distribution network (GDN) [7] consisting of 295 buses, 278 lines, and 39 transformers. A set of customer plants of different sizes, sensitive process characteristics and initial financial loss values per sag event is included to enhance the practicality of the assessment.

2. Optimal Monitor Placement for Fault Location

The problem of optimal monitor placement for fault location is defined as finding the minimum number and optimal locations for monitors in a system so that the system is completely observable. In a fault location sense, a system is fully observable if all faults occurring anywhere in the system are uniquely localized [6]. A fault that is uniquely localized is one for which only one fault location estimate is determined. In this approach, faults are located using the phasor-based algorithm proposed in [8] and briefly described next.

A. Fault Location Algorithm

Consider the sample network shown in Fig 1. Suppose that a fault takes place at point P on line connecting buses *j* and *k*; *d* is per unit fault distance from bus *j* and $z^{(s)}$ is the impedance of the line, with s = 0, 1, or 2 indicating zero, positive, or negative sequence impedance values. The sequence voltages at bus *i* can be calculated by

$$V_i^{(1)} = V_i^{(1)pf} - Z_{i\mathrm{P}}^{(1)} I_f^{(1)} \tag{1}$$

$$V_i^{(2)} = -Z_{i\mathrm{P}}^{(2)} I_f^{(2)} \tag{2}$$

$$V_i^{(0)} = -Z_{i\mathrm{P}}^{(0)} I_f^{(0)} \tag{3}$$

where $V_i^{(1)}, V_i^{(2)}, V_i^{(0)}$ are positive-, negative-, and zero-sequence voltage at bus *i* during the fault, respectively; $V_i^{(1)pf}$ is the pre-fault positive sequence voltage at bus *i*; $Z_{i\mathrm{P}}^{(1)}, Z_{i\mathrm{P}}^{(2)}, Z_{i\mathrm{P}}^{(0)}$ are the positive-, negative-, and zero-sequence transfer impedance between bus *i* and fault point P, respectively; and $I_f^{(1)}, I_f^{(2)}, I_f^{(0)}$ are the positive-, negative-, and zero-sequence current at fault point P, respectively.

For line to ground faults, $I_f^{(0)} = I_f^{(1)} = I_f^{(2)}$. Dividing (2) by (3) yields

$$\frac{V_i^{(2)}}{V_i^{(0)}} = \frac{Z_{i\mathrm{P}}^{(2)}}{Z_{i\mathrm{P}}^{(0)}} \tag{4}$$

where

$$Z_{i\mathrm{P}}^{(0)} = Z_{ij}^{(0)} + \left(Z_{ik}^{(0)} - Z_{ij}^{(0)}\right) d \tag{5}$$

$$Z_{i\mathrm{P}}^{(2)} = Z_{ij}^{(2)} + \left(Z_{ik}^{(2)} - Z_{ij}^{(2)}\right) d \tag{6}$$

Defining $G = V_i^{(2)} / V_i^{(0)}$ and utilizing (5) and (6), we get

$$G = \frac{Z_{ij}^{(2)} + \left(Z_{ik}^{(2)} - Z_{ij}^{(2)}\right) d}{Z_{ij}^{(0)} + \left(Z_{ik}^{(0)} - Z_{ij}^{(0)}\right) d} \tag{7}$$

The fault location is obtained solving (7)

$$d = \frac{Z_{ij}^{(2)} - G Z_{ij}^{(0)}}{G\left(Z_{ik}^{(0)} - Z_{ij}^{(0)}\right) - \left(Z_{ik}^{(2)} - Z_{ij}^{(2)}\right)} \tag{8}$$

Fault location equations for other types of faults and equations to calculate the fault impedance have also been formulated in [8]. One of the advantages of this algorithm is that the voltage measurement from bus *i* does not have to be from the faulted line and bus *i* can be distant from the faulted line. This characteristic has been exploited to develop an optimal monitor placement method for fault location in [6], which is summarized in the next section.

B. Optimal Monitor Placement

The optimal monitor placement problem for fault location has been formulated as an integer linear programming problem with the following objective function:

$$\text{Minimize} \sum_{x=1}^{N} c_x \mathbf{M}_x \tag{9}$$

subject to full fault observability of the system, where c_x is the cost of placing a monitor at bus x, $\mathbf{M}$ is a binary vector of length N whose entry $\mathbf{M}_x$ is 1 if a monitor is placed at bus x and is 0 otherwise, and N is the number of buses in the system.

The set of linear constraints that guarantee full fault location observability are derived from a list of pre-defined fault points and the combinations of monitors that can uniquely determine their location. Consider again the 4-bus network diagrammed in Fig. 1 to illustrate the procedure to formulate the linear constraints.

Assume that a line to ground fault is simulated at point P and residual voltages at all buses are calculated. Equation (8) is then solved for every line using the voltage at each bus, i.e. a total of four equations are solved. The solutions of these equations are next used to find the combinations of monitors that identify point P as the only or most likely fault location. Lastly, the linear constraints are derived from the combinations of monitors that can uniquely determine the actual fault point P.

As Fig. 1 shows, bus *j* estimates only one fault location whereas the rest of buses yield two estimates. The fault location estimate from bus *j* corresponds to the actual fault location. Buses *h*, *i*, and *k* also locate the fault correctly but not uniquely. Bus *k* estimates an additional fault location at point Q while buses *h* and *i* estimate a second fault location at point R. Accordingly, the sets of fault locations are S_h = {P,R}, S_i = {P,R} , S_j = {P}, and S_k = {P,Q} for buses *h*, *i*, *j*, and *k*, respectively.

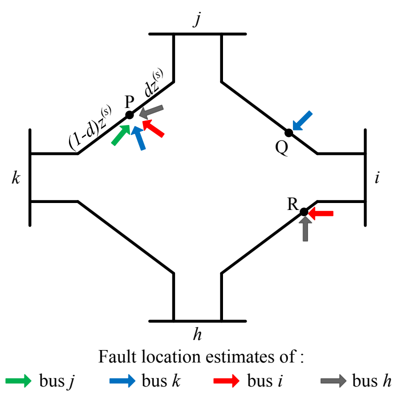

Fig. 1 Sample 4-bus network.

It is evident from these sets that the single element of S_j, the intersection of S_k and S_h, and the intersection of S_k and S_i, are equal to {P}, the actual fault location. Therefore, the combinations of monitors that can uniquely determine fault point P are {*j*}, {*h*,*k*}, and {*i*,*k*}, i.e., placing one monitor at bus *j*, or two monitors, one at bus *k* and the other at bus *h* or *i*, are sufficient to uniquely locate fault point P. Mathematically, this constraint can be represented as:

$$\mathbf{M}_j + \left(\mathbf{M}_h \wedge \mathbf{M}_k\right) + \left(\mathbf{M}_i \wedge \mathbf{M}_k\right) \geq 1 \qquad (10)$$

If constraint (10) is satisfied fault point P becomes observable. Since the overall aim of the optimization problem is the minimization of monitoring costs, one monitor at bus *j* would be chosen as the most economical monitor combination (from the three analyzed) that ensures observability of fault point P.

3. Voltage Sag Profile Estimation at Non-Monitored Buses

The number and characteristics of voltage sags at non-monitored buses can be estimated by network simulation using the fault location estimates obtained with the fault location algorithm presented in section 2.A. If the measurements used are from a full optimal monitoring scheme (see section 2.B), only one estimate for the fault location and for the fault impedance can be expected for any fault occurring throughout the network, which lead to virtually exact sag profile estimation. When measurements are taken from monitors at non-optimal locations or the monitoring scheme consists of fewer monitors than the minimum required for complete fault observability, most of the faults will have multiple estimates.

In the presence of multiple fault location estimates, faults are simulated at the potential locations and with the estimated fault impedance. The most probable fault location is the one which has the closest calculated residual voltages to the measured voltages by all monitors of the monitoring scheme.

4. Risk-Based Assessment of Financial Losses due to Voltage Sags

The methodology for analysis of financial losses caused by voltage sags proposed in [9] is implemented here due to its comprehensive risk-based approach. The methodology is focused on losses suffered by industrial plants and includes a probabilistic modelling of the main elements involved in the assessment of process-disruptive sags and the associated financial losses.

The financial loss incurred by an industrial plant due to each sag event is given by 11 [9].

$$\begin{pmatrix}\text{Financial}\\ \text{loss}\end{pmatrix} = \begin{pmatrix}\text{Process}\\ \text{failure}\\ \text{risk}\end{pmatrix} \times \begin{pmatrix}\text{Loss due to}\\ \text{process trip}\end{pmatrix} \qquad (11)$$

It can be seen from (11) that the two most important factors that determine the magnitude of financial loss are the failure risk of the industrial process and the losses incurred due to process trip. The main factors that influence industrial process failure risk are the sensitivity of customer equipment and processes and number and characteristics of sags at the customer site. The financial losses entailed by a process trip depend on the variation in process activity due to the process cycle and the plant's load profile.

For voltage sag financial analysis, the stochastic net present value (SNPV) method is incorporated in the methodology. SNPV is a modification of conventional net present value (NPV) method that includes risk representation in the analysis. This characteristic allows taking into account the non-deterministic nature of several components included in the analysis, such as process sensitivity and voltage sag profile.

The financial losses incurred by the industrial plant due to voltage sags can be calculated using the following equations [9]:

$$\text{SNPV} = \sum_{y=1}^{Y} \frac{\text{SCF}_y}{\left(1+\text{r}\right)^y} - I \qquad (12)$$

$$\text{SCF}_y = -\left(T_y + \sum_{s=1}^{S} p_s L_s\right) \qquad (13)$$

where

SCF_y	stochastic net cash flow at year *y*;
Y	project lifetime in years;
y	year number;
I	initial investment (if applicable);
r	discount rate;
S	total number of sags in year *y*;
s	sag number;
p	process failure risk, obtained from (11)
T_y	operation and maintenance cost of investment in year *y* (if applicable);
L	loss due to process trip, obtained from (11).

Although (12) and (13) were originally formulated to calculate the stochastic net present value of a sag mitigation option, they can be used to determine how much money could be lost without mitigation [9].

5. Case Studies

Assessment of financial losses due to sags has been undertaken using various monitoring schemes. The studies were performed on a generic distribution network (GDN) developed using typical parameters and configurations present in UK distribution networks. The network consists of a 400-kV transmission system in-feed, a predominantly meshed 33-kV network, and a predominantly radial 11-kV network. The network is solidly grounded and has 295 buses, 133 underground cables, 145 overhead lines, and 39 transformers with different winding connections. The network data is provided in [7]. All types of power system short circuit faults, i.e., line to ground (LG), line to line (LL), line to line to ground (LLG), and three-phase faults (LLL) were considered in the studies.

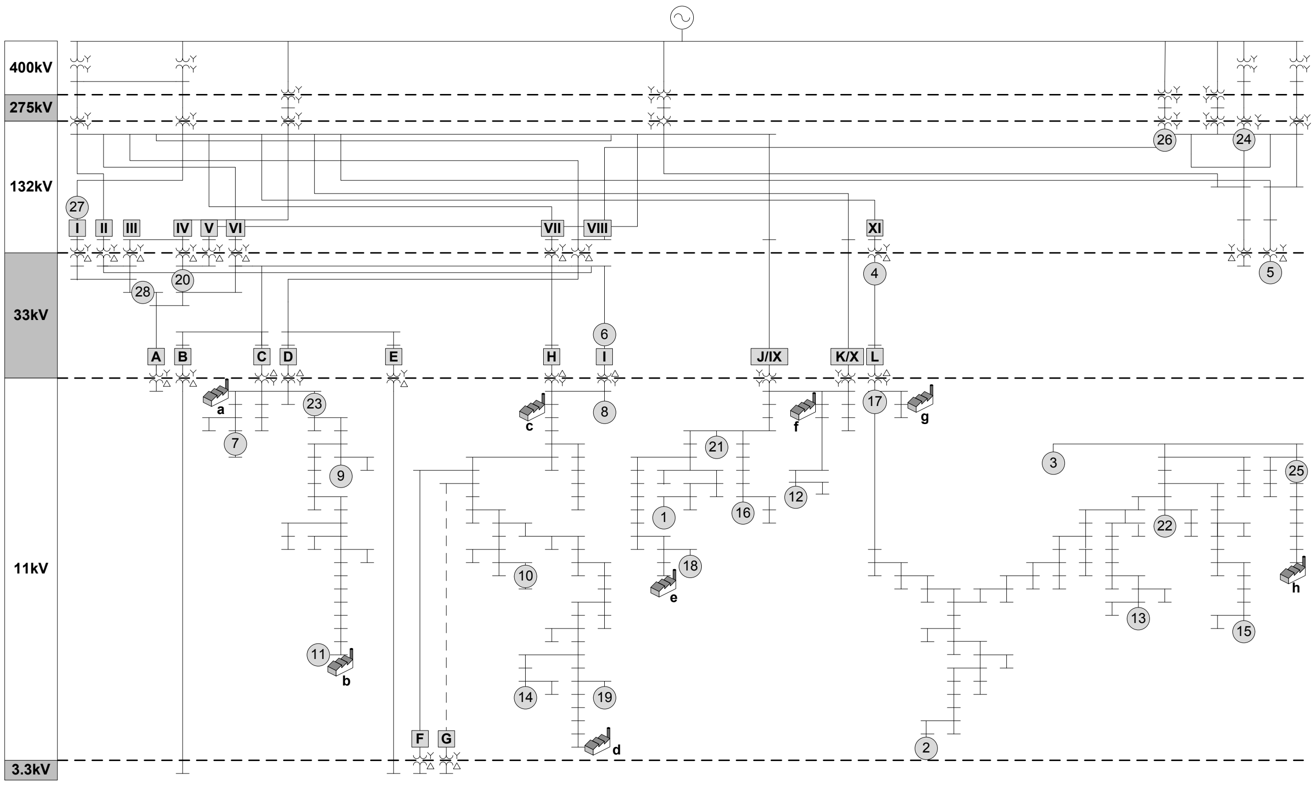

Fig. 2 Optimal sag monitoring scheme (28 monitors) and customer's plant locations in the generic distribution network.

A. Optimal Sag Monitoring Schemes

The minimum number and locations of monitors required to locate each and all types of faults were determined. Six fault points were simulated at 0.01, 0.206, 0.402, 0.598, 0.794, and 0.99 on each line and therefore the total number of fault positions is 1668. A total of 25 monitors is required to locate all line-to-ground faults. It was found that 5 monitors are sufficient to determine the location of line-to-line and three-phase faults, and that 21 monitors can estimate a unique location for line-to-line-to-ground faults. In order to pinpoint the location of all types of faults, 28 monitors need to be deployed in the GDN as shown in Fig. 2 with gray circles.

B. Assessment of Financial Losses

The methodology developed in [9] has been used to calculate the financial losses incurred by 9 different types of customer plants due to voltage sags. The plants' characteristics used in the assessment are shown in Table 1. The plants have financial loss specific to business type (ranging from less than £4.4k to more than £3M), different numbers of sensitive processes in each plant (from 1 to 8), and different types of sensitive equipment type.

Five sag monitoring schemes have been used during the financial loss assessment. Two of them represent the current practice in most parts of the world, where power quality monitoring takes place at HV/MV substations. These two monitoring schemes have been named 'eng1' and 'eng2'. Eng1 consists of 9 monitors placed at 132/33kV substations and 2 monitors located at 132/11kV substations. These substations are indicated in Fig. 2 by Roman numerals. Eng2 comprises 8 monitors installed at 33/11kV substations and 2 monitors placed at 132/11 kV substations. Capital letters indicate the location of these substations in Fig. 2. The remaining three sag monitoring schemes, named 'opt6','opt8', and 'opt10', correspond respectively to the first 6, 8, and 10 monitoring locations of the optimal monitoring scheme found in section 5.A and depicted in Fig. 2 with encircled Arabic numbers.

Eight different locations of customer plants have been considered in the assessments of financial losses. Plants are either located close to (locations a, c, f, and g) or far away from (locations b, d, e, and h) bulk supply substations (33/11kV).

Table 1 Customer Plant Characteristics, adopted from [4]

Customer	Business	Financial loss (£)/event	No. of sensitive processes	Sensitive equipment
1	Pulp and paper integrated	18300	5	AC contactors, ASD
2	Metal works	152500	4	ASD, PLC
3	Food processing	4366	3	ASD, PLC, AC contactors
4	Textile	15250	4	ASD, PLC, AC contactors
5	Semiconductor fabrication	3344000	8	ASD, PLC
6	Automotive assembly	45750	5	ASD, PLC, AC contactors, PC
7	Chemical	30500	2	ASD, PLC
8	Equipment manufacturing	61000	4	ASD, AC Contactors
9	Plastic extrusion	18300	1	ASD

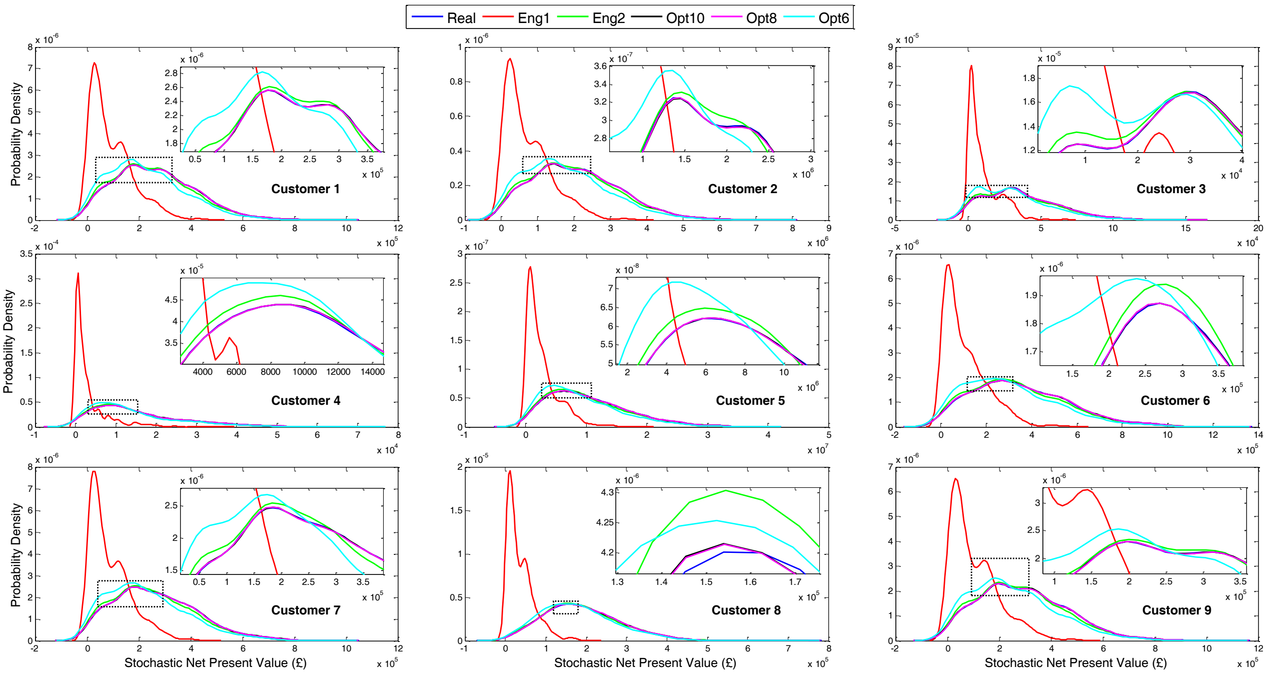

Fig. 3 Distribution of SNPV from 1000 trials for all customers' plants at location h estimated using all monitoring schemes.

Monte Carlo simulation of 1000 trials has been run for a one-year assessment period. The steps involved in the simulation are as follows [9]:

Step 1) Generate the annual number of faults using the data of Table 2.

Step 2) For each fault, estimate the fault location using the fault location algorithm of section 2.A and the five monitoring schemes.

Step 3) For each fault located, estimate sag characteristics at locations a – h.

Step 4) Run the sensitivity assessment for the 9 plants with the estimated sags as input. Obtain process failure for each sag, as required by (13).

Step 5) Calculate the Loss due to Process trip (L) using (11), with the data of Table 1.

Step 6) Calculate SNPV using (12) and ignore investment costs.

Step 7) Repeats Steps 1) - 6) for 1000 trials.

The distribution of financial losses due to voltage sags for all customers' plants attached to location h is shown in Fig. 3. Six graphs are plotted in each subfigure, five corresponding to the losses estimated using the aforesaid monitoring schemes and the sixth one representing the real losses; i.e., losses calculated assuming that a monitor is present at the customer busbar (location h).

As the overlapping of the blue (real), black (opt10 scheme), and magenta (opt8 scheme) graphs shows, 8 and 10 optimally placed monitors provide the most accurate results. The 10 monitors measuring voltages at both 33 kV and 11 kV voltage levels (eng2 scheme represented by green graphs) estimate the real amount of losses fairly accurately although they overestimate the probability of occurrence in most cases. Less accurate are the estimates derived from the first 6 monitors of the optimal sag monitoring scheme (opt6 scheme represented by cyan graphs), since the financial losses determined by this set of monitors tend to be lower than the real losses.

Finally, the least accurate results, represented by red graphs, came from the set of monitors installed at the 132 kV and 33 kV levels (eng1 scheme). The financial losses estimated by this monitoring scheme are practically nil for all customers. This is explained by the fact that 9 of the 11 monitors of eng1 scheme are situated at transformers with Wye-delta connections, which hinders the location of LG and LLG faults and these two types of fault constitute 90% of the total as indicated by Table 2. However, both of the remaining monitors of eng1 scheme are placed at Wye-wye transformers (substations IX and X)) and thus they can locate all types of faults occurring in this zone of the network (downstream of substations IX and X), accounting for all the losses greater than zero estimated by eng1 scheme.

Fig. 3 also shows that for most of the 1000 trials, the SNPV for customers 1, 2, and 3 is centred around £200k, £150k, and £30k, respectively. This means that these plants will lose every year an average present worth of £200k, £150k, and £30k, respectively, due to voltage sags. Similarly, the assessment of financial losses for customers 4, 5, and 6 shows that they will lose an annual average present worth of £9k, £6M, and £275k, respectively. The annual losses for customers 7 and 9 will average around £200k, and for customer 8 £160k.

The distribution of financial losses due to voltage sags for customer 5 (semiconductor factory) at every location (a to h) is shown in Fig 4. The first box plot in the subfigures represents the actual losses and the other five the losses determined using a specific monitoring scheme.

Table 2 System Fault Statistics, adopted from [7]

Fault rate/year				Fault distribution
Buses	Network 132 kV	Network 33 kV	Network 11 kV	
0.08	1.2	7.4	16.6	LG 73%, LL 6%, LLG 17%, LLL 4%

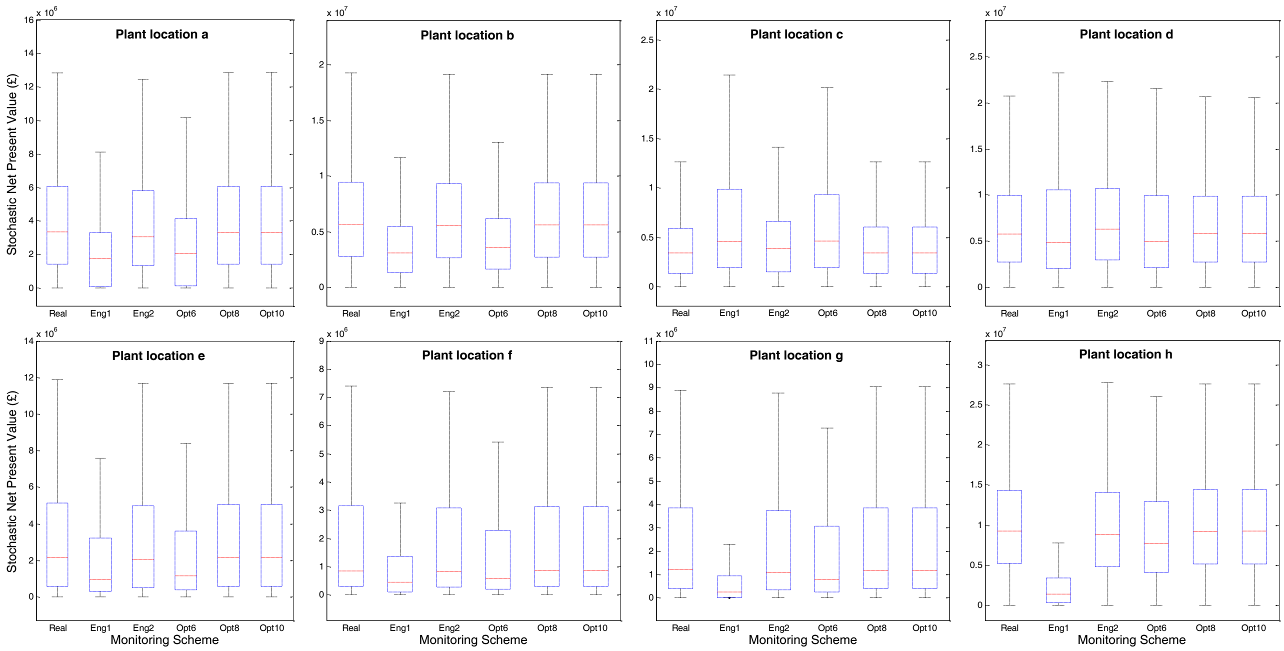

Fig. 4 Distribution of SNPV from 1000 trials for a semiconductor factory at all locations (a-h) estimated using all monitoring schemes.

As in the previous example, monitoring schemes eng2, opt8, and opt10 provide the most accurate results. These sets of monitors calculate almost exactly the median and the range of financial losses incurred at all locations. This is due to more comprehensive coverage by the three monitoring schemes in terms of fault location. Monitors belonging to schemes eng2, opt8, and opt10 cover the 11 kV and 33 kV networks, where the vast majority of faults were simulated, and therefore faults can be pinpointed leading to high accuracy in both voltage sag profile estimation and financial losses assessment.

A comparison between monitoring schemes shows that opt6 and eng1 provide the least accurate financial loss estimation and among the two, eng1 entails the biggest discrepancy between actual and estimated losses. This is due to the better fault location observability of the first six optimal sag monitoring locations (three 11kV buses and three 33 kV buses) than the eleven monitored substations (nine 132/33 kV and two 132/11kV) of scheme eng1.

Regarding the financial losses incurred by the semiconductor fabrication plant, which suffers the highest financial loss per event, the median annual losses range from less than £1 M to almost £10 M. It can be seen from Fig. 4 that locating the plant close to bulk supply substations (location a, c, f, g) entails lower financial losses than at the end of feeders (location b, d, e, h). (Please note difference in ordinate scale in Fig. 4)

6. Conclusion

This paper presented the use of optimal sag monitoring schemes for financial-loss analysis in voltage sag studies. A risk-based methodology was used to calculate the financial losses incurred by different sensitive customers due to voltage sags. The assessment of financial losses cause by sags is carried out by estimating voltage sag profiles at customer busbars, based on fault localization by a limited number of optimally placed monitors. It is shown that high accuracy in the assessment can be achieved when monitoring power quality in sites other that substations and with sag monitoring schemes partly deployed. The main factor influencing the effectiveness of sag monitoring schemes in the assessment of financial losses is the extent of their fault location observability area, which is greatly determined by the presence of transformers with delta connections.

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