Assessment of the Economic Value of Voltage Sag Mitigation Devices to Sensitive Industrial Plants

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***Abstract*—This paper investigates the economic value of voltage sag mitigation devices to end users. The focus is on sensitive industrial plants. Different types of power system faults are simulated on a typical British distribution network model to obtain voltage sag profiles at various locations in the network. The cost-effectiveness of various mitigation devices is investigated for industrial-size end users with various process characteristics and sensitivities, to obtain the optimal investment profile for each end-user plant. The sensitivity of the assessment to various levels of initial financial loss resulting from process interruption and network fault rates is also investigated. The findings would serve as valuable references for industrial end users who are considering investment in mitigation devices to reduce the financial losses caused by voltage sags.**

***Index Terms*—Power quality (PQ), risk analysis, voltage sag.**

I. Introduction

IT IS well established [1] that power-quality (PQ) problems, such as voltage sags and short interruptions, result in large financial losses to industrial and commercial establishments around the world. Investigations into custom power devices concluded that major financial savings can be achieved [2], [3] by industrial plant owners who operate sensitive industrial processes and experience frequent PQ-caused process outages (process trips). These findings strengthen the claim that for these customers, some form of mitigation is inevitable. However, at the present time, PQ mitigation practices are often dealt with on a plant-by-plant basis where overcompensation is not unusual. This is especially true when plant owners invest millions in devices that are not necessarily optimal in terms of economic benefits for their respective plants.

In the competitive business world, investment in PQ mitigation devices must be financially justified. This justification comes from potential financial savings from fewer process interruptions and improved operation predictability at end-user plants.

Over the years, numerous methods have been proposed to investigate the effects of voltage sags on industrial equipment [4]–[6], in estimating the financial losses due to voltage sags [7]–[9], in investigating the technical effectiveness of sag mitigation [2], [10], [11], and in developing general techniques for choosing the optimal mitigation device for end-user plants [12]–[14]. These studies have contributed tremendously in building the understanding of the phenomenon, of its impact to industries, and of options for mitigation. It should be mentioned though that many industries, particularly those employing highly sensitive equipment and processes and, therefore, potentially exposed to very high financial losses, for example, the semiconductor industry, adopted the immunity-first approach in commissioning equipment for their plants to ensure equipment immunity to external disturbances. This approach is discussed in detail in [15] and [16].

To ensure success in voltage sag investment projects, thorough risk and financial assessments are essential. This would involve a monitoring scheme to log and measure the voltage sag events at the point of connection of the end-user plant, and further analyses to assess the behavior of plant equipment and processes against these sags. However, in practice, overinvestment is often favored over proper assessment due to the inconvenience of prolonged measurement periods and complicated process susceptibility studies.

To avoid the wasteful approach of overinvestment, the authors investigate the effectiveness of various voltage sag mitigation devices, on a range of generic industrial plants, to establish a correlation between the value of these devices and the initial plant losses due to the sags.

For this purpose, a typical British distribution network has been modeled for the investigations. Using the method developed in [17] and [18], industrial plants of various process characteristics and sensitivities have been modeled and scattered across various locations in the network. Power system faults are then simulated at various locations in the network to create the voltage sag events experienced by the industrial plants, and to obtain the base-case financial loss for each plant. Common voltage sag mitigation devices are then modeled at the plants to investigate the cost-effectiveness of the devices, and to obtain the optimal investment profile (type and size of the device) for different plants.

By considering various characteristics of the industrial plants (nominal loss, equipment type, process immunity, process interdependency) and mitigation devices (device type and size), a correlation between the value of these devices and the initial plant losses can be made. With this correlation, plant owners could obtain a good indication of potential returns in voltage sag mitigation investment without the need for complicated studies as required in existing methods proposed by other researchers.

Manuscript received August 15, 2013; revised December 19, 2013, March 13, 2014, June 05, 2014, and July 22, 2014; accepted August 31, 2014. Date of current version November 18, 2015. This work was supported by E.On U.K. Paper no. TPWRD-00922-2013.

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Digital Object Identifier 10.1109/TPWRD.2014.2355877

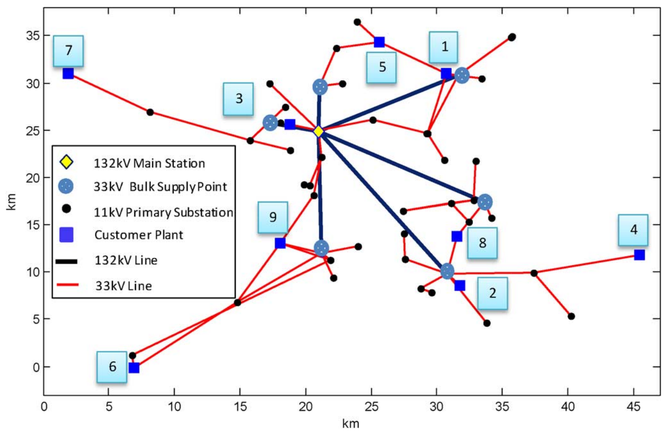

Fig. 1. Network model.

TABLE I
NETWORK FAULT RATES

Faulted Component	Voltage Level (kV)	Fault Rate (per km/annum) or (per bus/annum)			
		L-L-L	L-G	L-L-G	L-L
Bus	11, 33, 132	0.0032	0.0584	0.0136	0.0048
Overhead Line	11, 33	0.0087	0.1588	0.0370	0.0131
	132	0.006	0.1095	0.0255	0.0090
Underground Cable	11, 33, 132	0.002	0.0365	0.0085	0.0030

II. Study Case and Methodology

A. Network

A model based on an actual British distribution network is developed to facilitate the investigation. The network model consists of 158 buses; fifteen 132-kV buses, ninety six 33-kV buses, forty five 11-kV buses and two 6.6-kV buses. As illustrated in Fig. 1, the network has a total length of 521 km; 150 km of 132-kV lines and 371 km of 33-kV lines with a mixture of cables and overhead lines. System short-circuit power at the 132-kV main station is 927 MVA.

From the network, the authors selected nine locations for the placement of industrial plants. The locations are numbered in Fig. 1 and are chosen such that different areas of the network are represented. The industrial plants are either located close to (locations 1, 2, 3), far away from (locations 4, 6, 7) or in between (locations 5, 8, 9) bulk supply substations (33 kV). This is to consider the influence of plant proximity to strong supply buses.

B. Disturbances

Voltage sags are generated by simulating faults at all buses and lines in the network. The fault rates are shown in Table I and are simulated such that L-L-L, L-G, L-L-G, and L-L faults are 4%, 73%, 17%, and 6% of all faults in the network [2], [14], [19]. Network fault durations are based on typical fault clearing times in distribution networks [2], [14], [19]. The fault clearing times used are: 60 ms for buses; and 300, 150, and 80 ms for 11, 33, and 132 kV lines, respectively.

To ensure realistic assessment, a fault occurrence factor is randomly assigned to all buses and lines, such that

$$\mathrm{FR_{bus}} = \mathrm{FR_{base\_bus}} \times \mathrm{FF} \tag{1}$$

TABLE II
DESCRIPTION OF CUSTOMER PROCESS CHARACTERISTICS

Characteristic	Description	Model
Dominant Equipment Type	Microprocessors	>75% personal computers (PC) and progrmmable logic controllers (PLC)
	Drives and Motors	> 75% adjustable speed drives (ASD) and AC contactors (ACC)
Process Immunity	High	equipment trip causes <25% of all processes to trip
	Low	equipment trip causes >75% of all processes to trip
	Moderate	equipment trip causes between 25% and 75% of all processes to trip
Interdependence between Processes	Low	all sub processes affect less than 2 other sub-processes
	High	at least 1 sub process affects 2 or more other sub-processes
Nominal Loss	Small	£10k/MW or £30k per trip
	Moderate	£35k/MW or £105k per trip
	Large	£75k/MW or £225k per trip
	Very Large	£100k/MW or £300k per trip

TABLE III
DESCRIPTION OF PROCESS GROUPS

Group	Dominant Equipment	Process Immunity	Interdependence
1	Microprocessor	High	Low
2			High
3		Low	Low
4			High
5		Moderate	Low
6			High
7	drives and contactors	High	Low
8			High
9		Low	Low
10			High
11		Moderate	Low
12			High

$$\mathrm{FR_{line}} = \mathrm{FR_{base\_line}} \times l_{\mathrm{line}} \times \mathrm{FF} \tag{2}$$

where FR is the fault rate of the line or bus, l is the line length, and FF is the assigned fault occurrence factor.

Fault occurrence factors are either low (50% of $\mathrm{FR_{base}}$), normal (same as $\mathrm{FR_{base}}$), or high (150% of $\mathrm{FR_{base}}$).

C. Industrial Plants

To ensure that the main plant characteristics are considered, the industrial plants are divided into generic plants based on the dominant equipment type, process immunity, interdependence level, and nominal financial loss. A total of 48 representative plants are modelled to include all combinations of process characteristics. The process characteristics are described in Table II. The 48 plants are further divided into 12 groups based on their characteristics, as shown in Table III. All plants have a fixed total load of 3 MW and four processes. The power factor is assumed at 0.7.

The voltage sag behavior of the plant equipment is derived from voltage tolerance curves of sensitive equipment. Fig. 2 shows a typical equipment voltage tolerance curve. When a voltage sag occurs, the voltage sag magnitude and duration will dictate the behavior of the equipment involved.

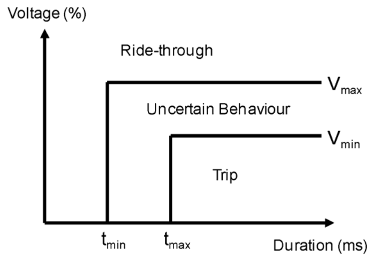

Fig. 2. General voltage sag tolerance curve for industrial equipment.

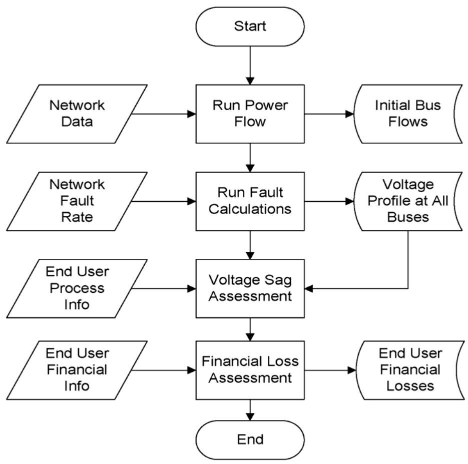

Fig. 3. Flowchart for end-user financial loss assessment.

If the voltage sag has a magnitude above $V_{\max}$ and a duration below $t_{\min}$, the equipment should ride-through the sag without tripping. The equipment will trip if the voltage sag magnitude is below $V_{\min}$ and the duration is above $t_{\max}$. For sags with magnitude between $V_{\min}$ and $V_{\max}$, and a duration between $t_{\min}$ and $t_{\max}$, the equipment behavior has to be further assessed. In such cases, this paper employs the probabilistic model developed in [18] to assess equipment and process failure.

D. Base-Case Financial Losses

Base-case financial loss is needed as the reference point for all assessments. Base-case loss is the financial loss suffered by an industrial plant due to the disturbances (voltage sags) simulated at the plant, before any mitigation device is installed. Fig. 3 shows the process flow for obtaining the base-case losses for the assessed plants. The base-case losses for the 48 assessed plants are summarized in Table V. The figures are based on financial losses for the next ten years converted to the present value, with a 6% discount rate. The values shown in Table V are the average values for the nine locations. It is found that financial loss could be as small as £0.1 M or as big as £24 M over ten years, depending on the characteristics and location of the industrial plant in the network. Plants with variable speed drives and contactors dominant processes tend to have larger losses compared to plants with microprocessor-dominant processes.

E. Mitigation Devices

Three commonly used power injecting devices for sag mitigation by industrial plants are investigated: the dynamic voltage restorer (DVR) with real and reactive power capability through battery storage, a DVR without real power storage, and an uninterruptible power supply (UPS) with flywheel energy storage. All three devices compensate for the depressed voltage during sag by injecting power into the point of connection from its stored energy.

TABLE IV
DVR Sizes Considered

Option	P_rated (MW)	Q_rated (MVAr)
1	0.25	1.0
2	0.50	1.0
3	1.0	2.0
4	1.5	2.0
5	2.0	3.0
6	3.0	4.0
7	4.0	5.0
8	5.0	6.0
9	6.0	7.0

1) DVR With Energy Storage: The dynamic voltage restorer (DVR) is a voltage injecting device connected in series to the protected load. It is typically of modular design and rated from 3 to 50 MVA [2], [14], [19] and usually has sufficient energy storage to compensate a 0.5 p.u. three-phase voltage sag for up to 10 cycles, the period required for fault clearance [19]. DVR provides voltage support almost instantaneously (typically within 1/4 of a cycle).

In this study, the DVR with prefault compensation control [19] is modeled to restore voltage magnitude and phase shift during sag. Considering a DVR with real and reactive power injection capabilities, both voltage magnitude and phase angle in all three phases can be restored independently to presag values. The maximum restorable voltage and phase angle depend on the P and Q ratings of the DVR. Nine different DVR sizes are considered in this study as shown in Table IV.

If the required real and reactive powers are within the capability of the DVR, full voltage restoration will be achieved, as given

$$\underline{V}_{\text{during\_sag}} = \underline{V}_{\text{pre\_sag}}. \tag{3}$$

However, if the sag is too severe, voltage will not be fully restored, as given in (4). The postfault voltage will have balanced voltages in all three phases (equal magnitude and phase-angle shifts) after mitigation

$$\underline{V}_{\text{during\_sag}} = \underline{V}_{\text{sag}} + \underline{V}_{\text{dvr}}. \tag{4}$$

2) DVR Without Energy Storage: A different DVR model with only reactive power injection capability is considered in the assessments. The DVR in this case will try to restore line voltages to prefault magnitudes, without real power (phase angle) injection capability.

3) UPS With Flywheel Storage: A flywheel is an energy-storage system that stores energy in the form of kinetic energy in its rotating mass. The amount of energy stored determines the duration that a flywheel system can support its protected load. In this study, the effect of a distribution voltage-level UPS with solid-state switching and supported by a flywheel energy-storage system is considered. During normal network operation, the sensitive load is supplied by the grid. In the event of a voltage

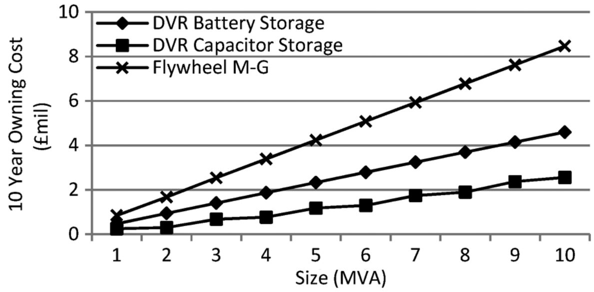

Fig. 4. Ten-year owning cost for mitigation devices.

sag in the main supply, the full load is transferred to the flywheel system within 1/4 of a cycle.

4) Device Costs: The total owning costs of the devices over a 10-year period are summarized in Fig. 4. All device costs are presented in present values [20] calculated using

$$C_{\text{device}} = C_{\text{initial}} + \sum_{n=1}^{N} \frac{C_{\text{annual}}}{(1+r)^n} \tag{5}$$

where C_{device} is the total owning cost over 10 years, C_{initial} is the initial capital investment, C_{annual} is the annual operating and maintenance costs, and r is the discount rate used for the present value calculations (6% used). Costs are calculated from year 1 (n) to year 10 (N).

The costs for a DVR with real and reactive capabilities are calculated based on cost information obtained from [19], with C_{annual} assumed at 10% of C_{initial}. The cost model for DVR with reactive power capability is based on cost information obtained from [21], with C_{annual} assumed at 5% of C_{initial}. The cost of a flywheel is determined by its energy storage capacity based on cost information obtained from [22]. This translates to an initial cost of £480/kVA plus 10% of assumed annual operation and maintenance costs, for 5 s of full-load protection.

III. Economic Value of Mitigation

The economic value of mitigation is determined by the savings achieved from the reduction in financial losses, as a direct result of installing a mitigation device, and the base-case financial loss. The value is calculated using (6) and (7). The resulting value from (7) is a present value, based on a 10-year assessment period, as a percentage of the base-case financial losses. In order to obtain the highest economic value for each solution, the savings have to be maximized. This is achieved by minimizing the postmitigation losses (remaining losses + mitigation cost), as iterated

$$\text{Savings} = L_{\text{base}} - (C_m + L_r) \tag{6}$$

$$\text{Value}(\%) = \frac{\text{Savings}}{L_{\text{base}}} \times 100\% \tag{7}$$

$$max\text{Savings} = min\left[PV\{C_m + L_r\}\right] \tag{8}$$

where L_{base} is the base-case plant financial losses before the mitigation device is installed; C_m is the cost of the mitigation device that include initial, operating, and maintenance costs; and L_r is the remaining sag losses postmitigation. PV represents the present value for the 10-year assessment period.

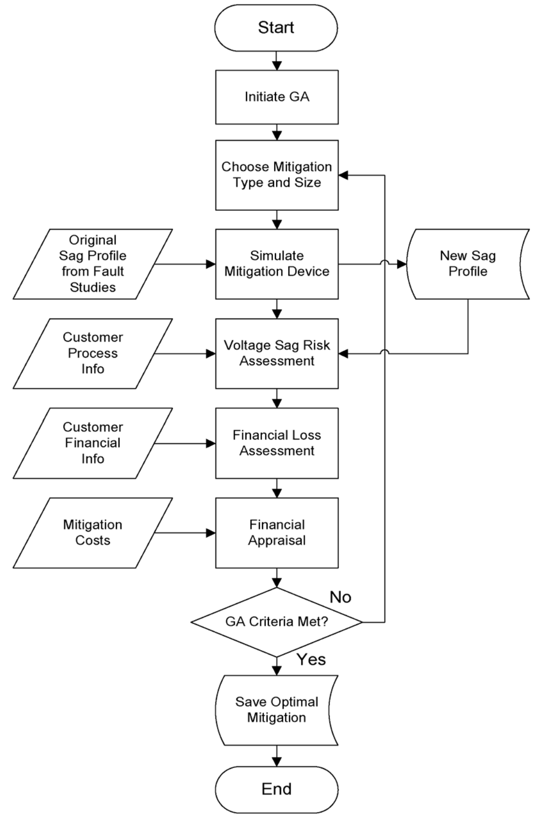

Fig. 5. Optimal mitigation device assessment flowchart.

For each of the 48 plants, the optimal mitigation type, the optimal number of mitigated processes in the plant, and the optimal device ratings need to be considered at all nine network locations. Due to the large number of possible input combinations involved, a genetic-algorithm (GA)-based optimization technique is used to find the optimal mitigation solution for each assessed plant.

Fig. 5 shows the simulation procedure required to determine the optimal mitigation solution for each plant. For each simulation, the GA tool will search for the optimal solution by selecting the best device type (DVR, DVR with capacitor storage, or UPS) for the plant, the optimal number of mitigated processes (all processes can be mitigated independently), and the optimal size of energy storage (Table III for the DVR). If a UPS was selected, the energy-storage size would be set to restore a complete loss of voltage for the mitigated processes, for a duration of 5 s.

Figs. 6 and 7 show the assessment results for microprocessor-dominant and drive-dominant plants, respectively, with optimal deployment of mitigation devices. The height of the bars represents the average base-case (unmitigated) financial loss for each assessed plant. With mitigation devices installed, the financial losses are reduced to the postmitigation losses (remaining losses + mitigation cost). The savings as a result of mitigation gives us the value of the mitigation device for the assessed plant. For example, Plant 15 in Fig. 6 has an average base-case (unmitigated) loss of £3.4 mil, reducing to £1.2 mil postmitigation.

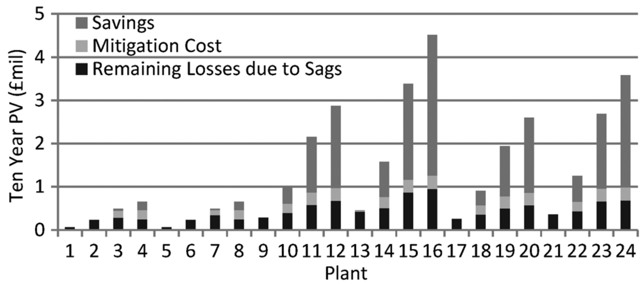

Fig. 6. Value of mitigation for microprocessor-dominant plants.

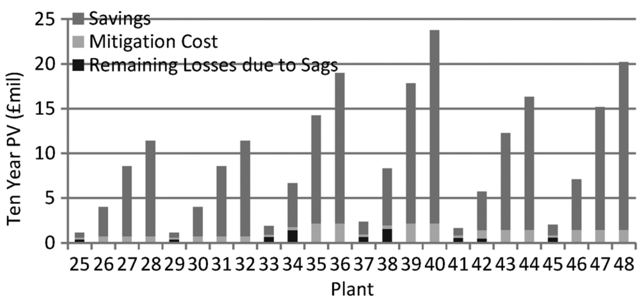

Fig. 7. Value of mitigation for drive-dominant plants.

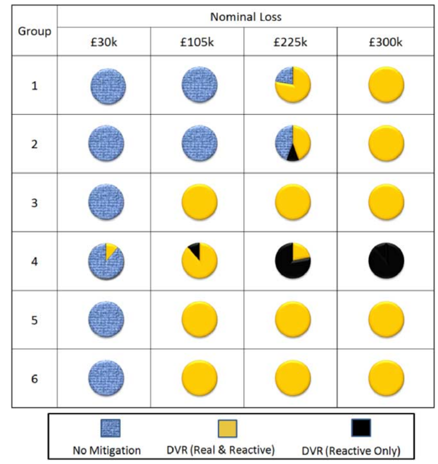

Fig. 8. Optimal mitigation device for microprocessor-dominant processes.

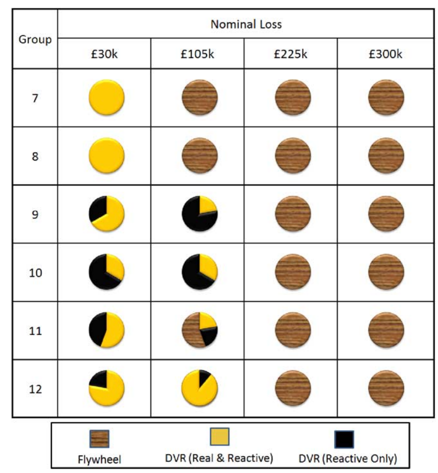

Fig. 9. Optimal mitigation device for drive-dominant processes.

This translates into £2.2 mil in savings, which represents the economic value of the mitigation device. The results are shown in detail in Table V.

It can be seen that postmitigation financial loss (remaining losses + mitigation cost) is capped at around £1 mil for microprocessor-based plants and around £2 mil for the drive-based plant over the ten-year period.

For microprocessor-based plants, postmitigation financial losses are mainly due to the remaining sags. There are also cases (i.e., Plants 9 and 13) where no savings can be achieved with mitigation devices; hence, none is selected.

For drive-based plants, however, postmitigation losses are mainly made up of the costs incurred to install the mitigation devices. Only a handful of plants (plants 34 and 38) still suffer from significant sag-induced losses. It should be noted that all financial values are referred to in present values, and in average values from the nine assessed network locations.

Figs. 8 and 9 show the optimal mitigation device for microprocessor-dominant and drive-dominant plants, respectively. The table rows represent different process groups (see Table III), while the columns represent the nominal loss per trip for each plant (see Table II). The pie charts show the distribution of optimal devices at various plant locations. It can be seen that the identical plants (identical group and nominal loss), located at different parts of the network, could employ very different mitigation devices. For example, consider the Group 11 (row 5) and low nominal loss plants (£30 k per trip, column 1) in Fig. 9. The corresponding pie chart shows that a DVR with real and reactive power capabilities is the best solution for the plant in five out of nine network locations (relative size of the yellow and black portions of the pie chart), while installing a DVR with reactive capability is best for the remaining four out of nine locations. However, if the nominal loss per trip is large (£300 k per trip, column 4), a UPS/flywheel system is the best solution at all nine network locations.

From the results, the following is evident:

- No savings can be achieved with voltage sag mitigation devices by microprocessor-dominant plants (Groups 1 to 6) that have low (£30 k), or moderate nominal loss per sag (£105 k) and high process immunity.
- For microprocessor-dominant plants where savings is achievable, DVR with real and reactive power capabilities is often the optimal device except for Group 4 (low immunity, high interdependence) plants where DVR with reactive power compensation is preferred.
- For drive-dominant plants (Groups 7 to 12) with small nominal loss per sag (£30 k), the best device can be either DVR with real and reactive power capabilities or DVR with reactive power capability, depending on the plant location in the network.
- For moderate nominal loss (£105 k) plants in Groups 7 to 12, the optimal device depends on process immunity and interdependence levels.
- For higher nominal loss (£225 k and above) plants in Groups 7 to 12, the UPS/flywheel is the most valuable mitigation device for voltage sag mitigation.

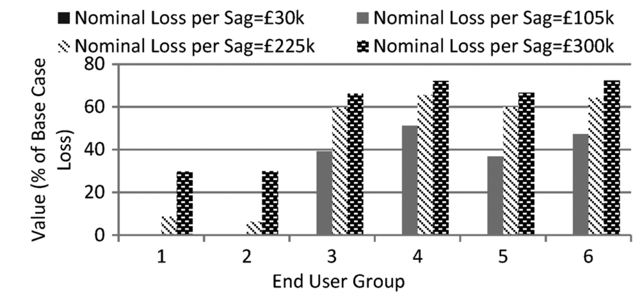

Fig. 10. Value of mitigation for microprocessor-dominant processes.

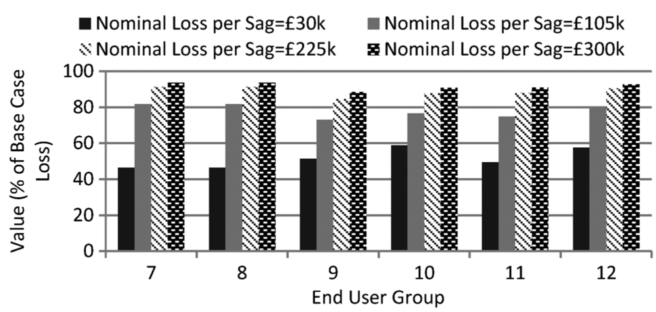

Fig. 11. Value of mitigation for drive-dominant processes.

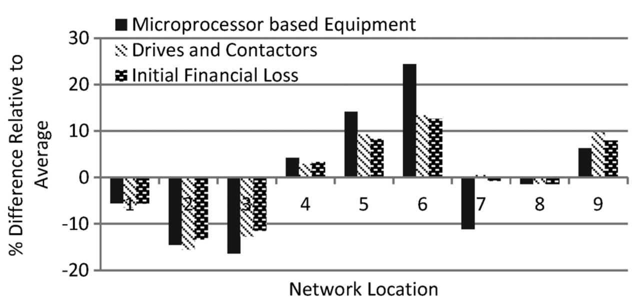

Fig. 12. Influence of network location on the value of mitigation.

A. Nominal Financial Loss Per Trip

The Nominal Financial Loss for a plant is the maximum financial loss the plant could suffer as a result of equipment/process trip due to a single voltage sag event. The majority of sags are not severe enough to cause all equipment/processes to trip. In such cases, the plant would suffer only a fraction of the Nominal Financial Loss. Figs. 10 and 11 show the value of mitigation devices to microprocessor-dominant and drive-dominant plants, respectively. It can be seen that for both types of plants, the value of mitigation increases with the increase in plant nominal loss.

The value of mitigation is significantly higher for drive-dominant plants compared to microprocessor-based plants. In the case of drive-dominant plants, the larger base-case financial losses opened up a wider choice of mitigation options that included more expensive but effective devices. On the other hand, the lower base-case losses of microprocessor-dominant plants could only produce limited savings when the same cost of mitigation is applied to (6).

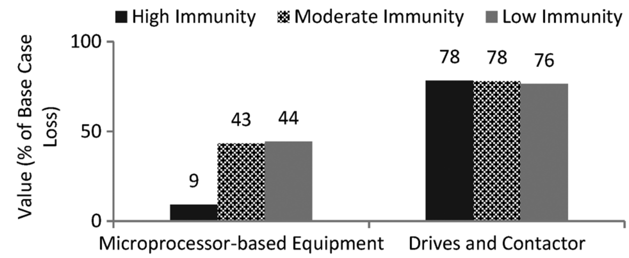

Fig. 13. Value of mitigation for different process immunity levels.

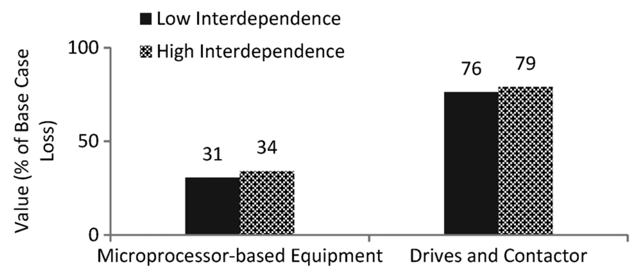

Fig. 14. Value of mitigation for different process interdependence levels.

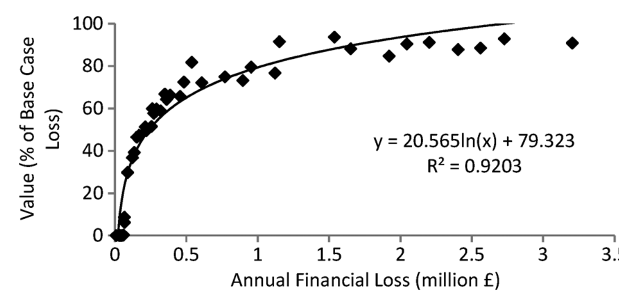

Fig. 15. Correlation between the value of mitigation and base-case loss.

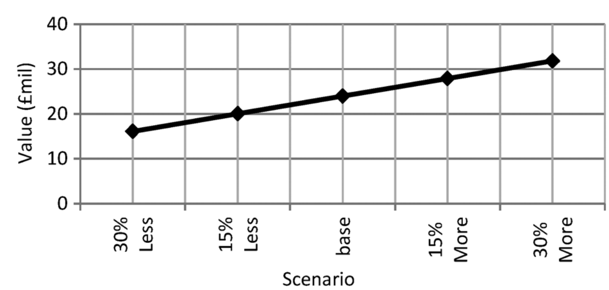

Fig. 16. Change in the value of mitigation for plant 40 at location 9 for a $\pm 30\%$ change in network fault rates.

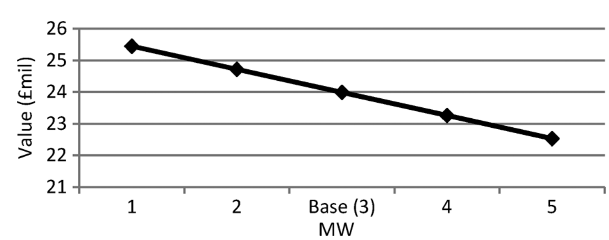

Fig. 17. Sensitivity of the value of mitigation to end-user plant size.

B. Location in the Network

Fig. 12 shows the variation in the value of mitigation, relative to the average value at all nine locations, for the assessed plants

TABLE V
LIST OF END-USER PLANTS AND THEIR CHARACTERISTICS

End User Plant	Group	Dominant Equipment	Process Immunity	Process Interdependence	Nominal Loss per trip ('000 £)	Average Base Case 10-year Loss ('mil £)	Average 10-year Value of Mitigation ('mil £)	Minimum, Combined 10-year Loss and Mitigation Cost ('mil £)
1	1	Microprocessor-Dominant	High	Low	0.030	0.1	0.0	0.1
2					0.105	0.2	0.0	0.2
3					0.225	0.5	0.0	0.5
4					0.300	0.7	0.2	0.5
5	2			High	0.030	0.1	0.0	0.1
6					0.105	0.2	0.0	0.2
7					0.225	0.5	0.0	0.5
8					0.300	0.7	0.2	0.5
9	3		Low	Low	0.030	0.3	0.0	0.3
10					0.105	1.0	0.4	0.6
11					0.225	2.2	1.3	0.9
12					0.300	2.9	1.9	1.0
13	4			High	0.030	0.5	0.0	0.5
14					0.105	1.6	0.8	0.8
15					0.225	3.4	2.2	1.2
16					0.300	4.5	3.3	1.3
17	5		Moderate	Low	0.030	0.3	0.0	0.3
18					0.105	0.9	0.3	0.6
19					0.225	2.0	1.2	0.8
20					0.300	2.6	1.7	0.9
21	6			High	0.030	0.4	0.0	0.4
22					0.105	1.3	0.6	0.7
23					0.225	2.7	1.7	1.0
24					0.300	3.6	2.6	1.0
25	7	Drive and Contactor-Dominant	High	Low	0.030	1.1	0.5	0.6
26					0.105	4.0	3.3	0.7
27					0.225	8.6	7.8	0.7
28					0.300	11.4	10.7	0.7
29	8			High	0.030	1.1	0.5	0.6
30					0.105	4.0	3.3	0.7
31					0.225	8.6	7.8	0.7
32					0.300	11.4	10.7	0.7
33	9		Low	Low	0.030	1.9	1.0	0.9
34					0.105	6.7	4.9	1.8
35					0.225	14.3	12.1	2.2
36					0.300	19.0	16.8	2.2
37	10			High	0.030	2.4	1.4	1.0
38					0.105	8.3	6.4	1.9
39					0.225	17.8	15.6	2.2
40					0.300	23.8	21.6	2.2
41	11		Moderate	Low	0.030	1.6	0.8	0.8
42					0.105	5.7	4.3	1.4
43					0.225	12.3	10.8	1.5
44					0.300	16.3	14.9	1.5
45	12			High	0.030	2.0	1.2	0.9
46					0.105	7.1	5.6	1.5
47					0.225	15.2	13.7	1.5
48					0.300	20.2	18.8	1.5

when located at each network location. The difference in value can be as high as 40% for microprocessor-dominant plant and 29% for drive-dominant plants between different network locations. The general trend in the losses is similar for both plant types across all network locations, indicating lower financial losses at locations closer to bulk supply substations (location 1, 2, 3), and above average losses at all other locations.

C. Immunity Levels of the End-User Process

Fig. 13 shows the relationship between the value of mitigation devices and the immunity level of processes at the assessed plants. The average values of all 48 plants at all nine network locations are shown. A 378% leap in value from high immunity processes to moderate immunity processes can be seen in the microprocessor-dominant plant. This is mainly due to the leap in base-case financial losses when process immunity changes. The difference between moderate immunity and low immunity processes is negligible.

For drive-based plants, the value of mitigation devices is not sensitive to the immunity level of their processes.

D. Interdependence Between Processes

Fig. 14 shows the relationship between the value of mitigation devices and the interdependence level between processes in the assessed plants. An average increase of 3% in value is observed for microprocessor-dominant and drive-dominant plants when process interdependency increases.

E. Base-Case Financial Loss

By performing a least square regression on the assessment results, the correlation between the value of mitigation devices and annual base-case plant losses is established. As shown in Fig. 15, the relationship is well represented (R^2 close to 1) by a logarithmic function. The regression model can be applied in cases where annual base-case losses are less than £2.9 mil. Cases with annual base-case plant losses of more that £2.9 mil would produce economic values exceeding 100%, which is impossible to achieve in practice.

F. Sensitivity to Network Fault Rates

Higher network fault rates would increase the number of voltage sags in the network, and would result in more process trips and more financial losses to the plant owners. Fig. 16 shows the change in the value of mitigation for Plant 40 at location 9 for varying network fault rates. With base-case losses of £26 M over ten years, a UPS/flywheel remains the optimal device for a $\pm 30\%$ change in network fault rate. For this plant, there is a linear relationship between the value of mitigation and the network fault rate of a 1.1% increase/decrease in value for every 1% increase/decrease in fault rate.

G. Sensitivity to End-User Plant Size

The study used a standard plant size of 3 MW in the assessments. If the size of the mitigated plant is different, the ratings and stored energy for the mitigation devices would change, so would the cost of the device. Fig. 17 shows the change in value for Plant 40 at location 9 for varying plant size. The value of mitigation is found to be inversely proportional to the mitigated plant size. The relationship is linear with a 3% decrease/increase in value for every 1 MW increase/decrease in plant size.

IV. Conclusion

The value of common custom power devices for voltage sag mitigation, including DVR with active and reactive power capabilities, DVR with reactive power capability, and UPS with flywheel storage has been investigated. Based on simulation results on a typical British distribution network, it is found that the value of mitigation depends on the nominal financial loss per process trip, the location of the plant in the network, and the immunity and interdependence levels of the processes.

There is a correlation between the value of mitigation and the annual plant base-case financial loss. This correlation can be represented with a logarithmic function and is sensitive to the network fault rate and the end-user plant size. The value of mitigation increases by 1.1% per 1% increase in fault rate and decreases by 3% per megawatt increase in plant size.

This paper considered three common devices for mitigating the voltage sags. The inclusion of a larger pool of mitigation devices would potentially result in a more refined correlation and should be investigated in future studies.

References

[1] R. Targosz and J. Manson, "Pan European LPQI power quality survey," presented at the CIRED 19th Int. Conf. Elect. Distrib., Vienna, Austria, 2007.
[2] J. V. Milanovic and Y. Zhang, "Modelling of FACTS devices for voltage sag mitigation studies in large power systems," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 3044–3052, Oct. 2010.
[3] C. D. C. Teixeira, "Power quality solutions for low and medium voltage critical loads," in *Proc. IEEE/Power Eng. Soc. Transm. Distrib. Conf. Expo.: Latin Amer.*, 2004, p. 326.
[4] S. Ž. Djokić, K. Stockman, J. V. Milanović, J. J. M. Desmet, and R. Belmans, "Sensitivity of AC adjustable speed drives to voltage sags and short interruptions," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 494–505, Jan. 2005.
[5] S. Z. Djokić, D. S. Kirschen, and J. V. Milanović, "Sensitivity of AC coil contactors to voltage sags, short interruptions, undervoltage transients," *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1299–1307, Jul. 2004.
[6] S. Ž. Djokić, J. Desmet, G. Vanalme, J. V. Milanović, and K. Stockman, "Sensitivity of personal computers to voltage sags and short interruptions," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 375–383, Jan. 2005.
[7] *IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment*, IEEE Standard 1346-1998.
[8] S. Quaia and F. Tosato, "Interruption costs caused by supply voltage dips and outages in small industrial plants: A case study and survey results," *Proc. IEEE Region 8 EUROCON*, vol. 2, pp. 258–262, 2003.
[9] S.-A. Yin, R.-F. Chang, and C.-N. Lu, "Reliability worth assessment of high-tech industry," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 359–365, Jan. 2003.
[10] A. Elnady and M. M. A. Salama, "Unified approach for mitigating voltage sag and voltage flicker using the DSTATCOM," *IEEE Trans. Power Del.*, vol. 20, no. 2, pt. 1, pp. 992–1000, Apr. 2005.
[11] B. Rogers, M. Stephens, and P. E. M. McGranaghan, "Power quality issues and solutions in the automotive industry," in *Proc. POWERCON*, Singapore, 2004, vol. 1, pp. 238–243.
[12] M. McGranaghan and B. Roettger, "Economic evaluation of power quality," *IEEE Power Eng. Rev.*, vol. 22, no. 2, pp. 8–12, Feb. 2002.
[13] D. V. Hertem, M. Didden, J. Driesen, and R. Belmans, "Choosing the correct mitigation method againsts voltage dips and interruptions: A customer based approach," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 331–339, Jan. 2007.
[14] J. V. Milanovic and Y. Zhang, "Global minimization of financial losses due to voltage sags with FACTS based devices," *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 298–306, Jan. 2010.
[15] J. Y. Chan and J. V. Milanović, Risk Based Evaluation Of Investment In Voltage Sag Mitigation CD Rom of the CIRED 2009, June 8–11, 2009. Prague, Czech Republic, (paper 0546).
[16] GRE/CIRED JWG C4.107, Economic Framework for Power Quality Jose Gutierrez Iglesias (Convenor), Detmar Arlt, Gerhard Bartak, Math Bollen, Dave Byrne, David Chapman, Alice Delahunty, Philippe Eyrolles, Elena Fumagalli, Mats Hager, Zbigniew Hanzelka, Bill Howe, Rafaël Jahn, Alex McEachern, Ian McMichaes, J. V. Milanović, Patxi Pazos, Roman Targosz, Mario Tremblay, Jasper Van Casteren, Mathieu Van Den Bergh, Raghavan Venkatesh. Paola Verde, (467), 978-2-85873-157-2, Jun. 2011.
[17] 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.
[18] J. Y. Chan, J. V. Milanovic, and A. Delahunty, "Generic failure risk assessment of industrial processes due to voltage sags," *IEEE Trans. Power Del.*, vol. 24, no. 4, p. 2405, Oct. 2009.
[19] Y. Zhang, "Techno-economic assessment of voltage sag performance and mitigation," Ph.D. dissertation, School Elect. Electron. Eng., University of Manchester, Manchester, U.K., 2008.
[20] A. Baggini and F. Bua, "Costs: Investment analysis for PQ solutions," *Leonardo Power Qual. Initiative*, Jul. 2004.
[21] W. E. Brumsickle, R. S. Scheider, G. A. Luckjiff, D. M. Divan, and M. F. McGranaghan, "Dynamic sag correctors: Cost effective industrial power line conditioning," *IEEE Trans. Ind. Appl.*, vol. 37, no. 1, pp. 212–217, Feb. 2001.
[22] R. R. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, 2nd ed. New York, USA: McGraw-Hill, 2002.

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