Probabilistic Assessment of Financial Losses in Distribution Network Due to Fault-Induced Process Interruptions Considering Process Immunity Time

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***Abstract*—This paper introduces a stochastic methodology to assess annual performance of distribution network and individual customers with respect to voltage sags, long duration interruptions, equipment trips, and process trips. These values are then used to evaluate financial losses in the entire distribution network. For each of the large number of simulated faults throughout the network, a probability of sag and long duration interruption occurrences is evaluated at each network bus. The methodology then includes for the first time the concept of process immunity time in order to assess as accurately as possible the resulting financial loss due to process interruption. To increase the accuracy of the assessment of financial loss, the methodology also considers the possibility of equipment and process restart, reliability, and type of fault. The methodology is illustrated on a real distribution network and it shows that inclusion of PIT in financial loss assessment results in a reduction of about 25% in estimated financial loss.**

***Index Terms*—Financial losses, power quality (PQ), process immunity time, reliability, voltage sags.**

I. Introduction

PROBLEMS resulting from the inadequate quality of electricity supply (power quality) typically lead to significant financial losses to costumers and the network as a whole. The most significant contributor to these financial losses is process interruptions resulting from voltage sags (or only sags) and long duration interruptions (LDIs). Equipment, such as contactors (C), personal computers (PCs), programmable logic controllers (PLCs), and adjustable speed drives (ASDs) have proven to be highly sensitive to voltage sags. These devices may fail, maloperate, or be disconnected by a protection system when subjected to brief reduction in the voltage magnitude. Commonly, the processes and activities of different types of customers (industrial, commercial, residential, etc.) are controlled/interfaced by these devices connected in different configurations. Thus, the failure of one device may cause a cascading failure of the entire production process or activity. In other words, the economic losses start with the process interruption and continue until the process comes back to its normal operation. An example of these losses in an industrial customer is shown in [1]. A sag of 1-s duration led to process interruption and 7-h delay to restart the process, resulting in a financial loss of approximately U.S.$35 k, taking into account lost production costs, overtime, and restarting production.

There are two main ways to assess financial loss. The first involves power-quality (PQ) monitoring at the customer connection point [1]–[3] and the second one is computer simulation of sags and process interruptions across the network. For the second approach, different strategies, including ones that use historic network performance data, have been developed in the past [4]–[6].

To assess financial losses of end-use customers, it is very important to understand the response of the equipment when exposed to sags. The "voltage-tolerance curve" or "sensitivity curve" is commonly used for this purpose. As reported in [7], this curve shows which combinations of sag magnitude and sag duration, as two most prominent sag characteristics, can affect the normal functioning of equipment. In order to account for a wide variety of equipment and their different sensitivity to sags, an uncertainty region or "voltage tolerance band" has been used [4], [8], [9] when defining equipment tolerance to sags. Furthermore, end-use customers use different groups of electric-electronic equipment in their processes and a single voltage tolerance curve is not representative enough of process sensitivity/failure—which ultimately causes financial loss. A sag at the customer connection point may cause a trip of a single device which ultimately could cause a trip of the entire process [10]. The identification of the device that could cause a trip is a difficult task because there are several devices that interact with each other and their impact, on the entire process, or part of it, is not always easy to track down and understand [10]. Considering this [11], [12], propose a general framework to assess the process performance against sags and introduce a concept of process immunity time (PIT) in order to identify the most critical devices within a given process.

The process immunity time (PIT) is defined as "*the time interval between the start of the voltage interruption and the moment the process parameter goes out of the allowed tolerance limit (i.e., below the threshold)*" [11]. In other words, when a sag

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or short or long duration interruption causes electrical device to stop functioning as intended (or to get completely disconnected from supply), this still does not mean that the process controlled by this device will get interrupted at the same time. The PIT will ultimately define whether the whole process is going to shut down as well. Using PIT as a reference, it is possible to assess if the process is capable of operating without supply voltage for a period of time longer than the duration of sag or interruption. If the normal supply comes back before the PIT and the electrical equipment interfacing the process can be restarted automatically, the process can withstand this perturbation. If the supply comes back after the PIT, the process will be interrupted and would require complete or partial restart. The process interruption effectively results in financial losses [11].

This paper introduces for the first time a methodology that incorporates PIT, together with improved modelling, of some of previously considered phenomena, including uncertainty of equipment sensitivity curves, probability of failure of protection devices, customer activity at the time of fault, and probability of automatic restart of equipment or processes following a brief interruption, into a single framework for the assessment of financial losses due to fault-induced industrial/commercial process interruptions. The application of the proposed framework is illustrated on a real distribution network.

II. Estimation of Process Trip Probability Due to Voltage Sags and Long Duration Interruptions

Power networks are continually exposed to short-circuit faults characterized by fault position, type of fault, fault impedance, and fault duration. If not directly available, these parameters can be estimated to a high degree of accuracy using probability distribution curves obtained from historical data. This paper uses a hybrid method proposed in [5] to obtain a set of short-circuit conditions (faults) in a distribution network. The impact of each fault on industrial/commercial processes is then analyzed to estimate the annual number of potential process trips.

A. Probability of Voltage Sag and LDI

To evaluate the annual number of sags and LDIs that a customer might be exposed to, it is essential to establish whether a fault in the network causes a sag or an LDI at the consumer connection point.

A short duration fault will typically cause a sag. The probability of this type of event can be estimated using the cumulative probability curve of voltage sag duration (CPSD). This curve can be obtained using historical data as discussed in [5] and [13]. On the other hand, when a fault lasts longer, customers can be disconnected and subjected to a loss of supply, that is, LDI. For a fault leading to LDI, the location of the protection device that isolates the fault and its curve of time current of protection (CTCP) is also referred to as a time–current curve [14], which defines the set of customers who will be disconnected after the fault.

In order to estimate the probability of sag (P_{sag}), swell (P_{swell}), and LDI (P_{LDI}), both curves—CTCP and CPSD—are used. For a particular fault characteristic (fault position, type of fault and impedance of fault), short-circuit current (I_I) is

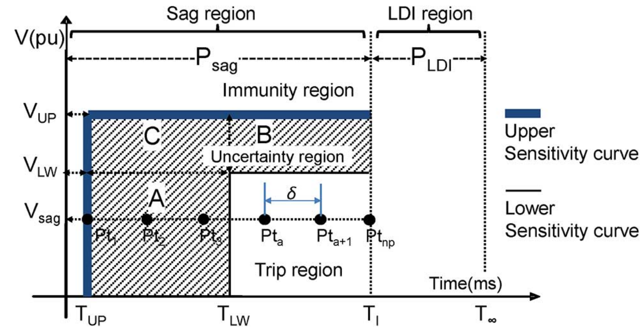

Fig. 1. Evaluation of equipment trip probability considering an uncertainty region between an upper and a lower sensitivity curve.

evaluated first. Following this, the CTCP of the protection device (PD) is used to determine the protection operation time (T_I) based on current I_I. If the duration of the fault is below T_I, customers downstream of PD will only experience a voltage sag. On the other hand, if the duration is longer than T_I, customers downstream of PD will experience an LDI. Customers upstream of PD will experience a sag with a duration of T_I. Finally, CPSD uses T_I to determine $P_{\text{sag}}(T_I)$, $P_{\text{swell}}(T_I)$, and $P_{\text{LDI}}(T_I)$ values for each fault [5]. Although it is possible to analyze voltage swells in a similar way, this paper focuses on analyzing voltage sags only due to their higher influence on sensitive equipment.

In order to simplify the analysis, without any loss of generality, this method assumes that short duration interruptions do not result in LDI to customers but instead have a probabilistic value, the same as sags.

Fig. 1 illustrates the assessment procedure. From Fig. 1, following the criteria presented before, two important regions can be distinguished: 1) the sag region and 2) the LDI region. Before the time T_I, equipment may be affected by sag (supply voltage $\neq$ zero), but after T_I, equipment are only affected by LDI (supply voltage $=$ zero). Thus, analyzing both regions, it is possible to assert that $P_{\text{sag}}(T_I) + P_{\text{LDI}}(T_I) = 1$ [5]. The variables V_{UP}, T_{UP}, and V_{LW} and T_{LW} represent voltage and time, respectively, related to an upper and a lower voltage sensitivity curve, respectively (i.e., bounds of the area of uncertainty of the voltage sensitivity curve). The letters A, B, and C define different subregions inside the voltage sensitivity curve uncertainty region. The application of these subregions is explained in more detail in the following sections. The variable V_{sag} represents a sag magnitude and the set of points $Pt_1, Pt_2, Pt_3, \ldots, Pt_a, Pt_{a+1}, \ldots, Pt_{np}$ refers to sags with magnitude V_{sag} and different durations inside the uncertainty region and the trip region. Index a represents a sag Pt_a between Pt_1 and Pt_{np}. The variables δ and np are the time steps between two consecutive points Pt_a and Pt_{a+1} and the number of points between T_{UP} and T_I, respectively.

B. Probability of Equipment Trip Due to Voltage Sag

In order to understand if equipment is affected by sags, manufacturers have been developing sensitivity curves for each device. Due to the large number of different devices, even though they could be of the same brand or category, it is very difficult, if not impossible, to define a single voltage sensitivity curve.

One way to model the voltage sensitivity curves of different devices is to establish an uncertainty region between an upper and lower voltage sensitivity curve [4] as shown in Fig. 1. Each subregion (A, B, and C, see Fig. 1), inside the uncertainty region has different corresponding probability density functions. In subregion A, the time varies between T_{UP} and T_{LW} while the magnitude is fixed at V_{LW}; in subregion B, the magnitude varies between V_{UP} and V_{LW} while the time fixed at T_{LW}; in subregion C is magnitude and time varying within V_{UP} and V_{LW} and T_{UP} and T_{LW}, respectively. Thus, considering that the probability density function of time $f_X(T)$ and voltage $f_Y(V)$ are stochastically independent, the uncertainty of equipment trip $(Un_{\mathrm{ET}}(T,V))$ for one sag position defined by (T,V) can be evaluated by (1) based on the *Bayesian rule* [4]

$$Un_{\mathrm{ET}}(T,V) = f_{XY}(T,V) = f_X(T)f_Y(V) \tag{1}$$

where from Fig. 1, $f_Y(V)=1$ for any T value in subregion A and $f_X(T)=1$ for any V value in subregion B [4].

The evaluation of equipment trip probability correlating a representative sensitivity curve and a CPSD is proposed in [5]. It is important to highlight though that the method proposed in [5] does not consider the effect of uncertainty of sensitivity curves on equipment trip.

Fig. 1 also shows regions of immunity to sags and region of equipment trip. The first one, above the upper sensitivity curve and before T_I, represents an event which does not affect the normal equipment function. In contrast, the trip region represents events which may lead to equipment trip because of a combination of V_{sag} and any time value between T_{LW} and T_I. For each time value T, two values may be calculated: $Un_{\mathrm{ET}}(T,V_{\mathrm{sag}})$ and $P_{\mathrm{sag}}(T)$. The correlation of these values to assess the probability of equipment trip and considering the uncertainty of sensitivity curves (P_{ETU}) is given by

$$\begin{aligned} P_{\mathrm{ETU}}(V_{\mathrm{sag}}) = \sum_{a=1}^{np-1} & \left[\left(P_{\mathrm{sag}}\left(T_{(a+1)}\right) - P_{\mathrm{sag}}\left(T_{(a)}\right)\right)\right. \\ & \left.\times Un_{ET}\left(T_{(a)},V_{\mathrm{sag}}\right)\right] \\ np = \mathrm{Integer}\left[\frac{(T_I - T_{UP})}{\delta}\right]; & \quad T_{(a+1)} = T_{(a)} + \delta \end{aligned} \tag{2}$$

where a is a sag inside the sensitivity curve with magnitude V_{sag} and duration $T_{(a)}$ ($Pt_{a,}$ in Fig. 1). A recommended value for δ is 10 ms [7]. Even though with lower values of δ, the P_{ETU} value would be slightly more accurate, more points would have to be evaluated, and the computational burden increased without significantly increasing overall accuracy of the assessment. $Un_{\mathrm{ET}}(T_{(a)},V_{\mathrm{sag}})$ can be obtained by (1) and $P_{\mathrm{sag}}(T_{(a)})$ by defined CPSD. For any point inside the trip region, $Un_{\mathrm{ET}}(T,V)=1$.

C. Probability of Process Trips Due to Voltage Sag

The probability of trip of the entire process can be obtained by considering the probability of trip of individual equipment (C, PC, PLC, or ASD) and their mutual connections (serial or parallel). The methodology to do so is originally proposed in [4] and [15] and modified here in order to consider cumulative probability values and the uncertainty of the sensitivity curves. A new formulation of uncertainty of process trip $(Un_{\mathrm{PT}}(T,V))$ considering different pieces of equipment involved, using (1), is given by

$$Un_{\mathrm{PT}}(T,V) = 1 - \left[\prod_{i=1}^{m}\left(1 - \prod_{j=1}^{n} Un_{\mathrm{ET}}(T,V)_{i,j}\right)\right]. \tag{3}$$

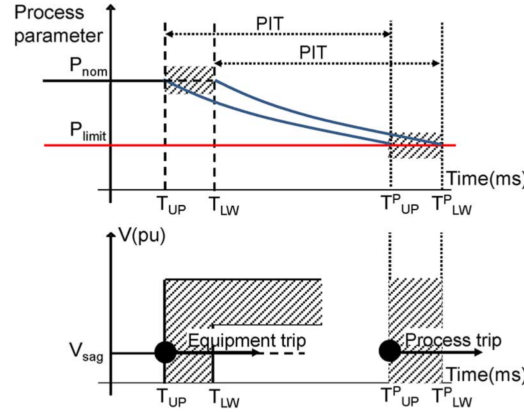

Fig. 2. Process immunity time (PIT) for equipment within a process considering the uncertainty region.

As defined in [15], m is the number of series-connected equipment and n is the number of parallel-connected equipment while i and j are corresponding counting indices.

By combining (2) and (3), the probability of process trip and considering the uncertainty of sensitivity curves due to sag (P_{PTU}) can be calculated as shown by (4). Even though (4) effectively integrates the methods proposed by [4] and [5] and such represents an advancement compared to either of them, it still assumes that equipment trip will lead directly to process trip, that is, it does not consider PIT (resilience of process failure to failure of electrical equipment interfacing the process)

$$\begin{aligned} P_{\mathrm{PTU}}(V_{\mathrm{sag}}) = \sum_{a=1}^{np-1} & \left[\left(P_{\mathrm{sag}}\left(T_{(a+1)}\right) - P_{\mathrm{sag}}\left(T_{(a)}\right)\right)\right. \\ & \left.\times Un_{\mathrm{PT}}\left(T_{(a)},V_{\mathrm{sag}}\right)\right]. \end{aligned} \tag{4}$$

III. Evaluation of Process Trip Probability by Applying Process Immunity Time

In order to describe the inclusion of PIT in assessment of the process trip, Fig. 2 is split in an upper part and a lower part. The upper part represents the behavior of a representative process when it is exposed to voltage sags. For that process, P_{nom} is a nominal process parameter, such as tight speed or position control, accurate temperature control, fluid level and flow rate control, air fans, etc. P_{limit} is the allowed tolerance limit of a process parameter.

The lower part of Fig. 2 shows the uncertainty of the sensitivity curve of the equipment that controls that process and the instants of the beginning of the equipment trip (i.e., T_{UP}) and process trip ($T_{\mathrm{UP}}^{\mathrm{P}}$) depending on the uncertainty of sensitivity curve. At the occurrence of a sag (or a short interruption) with a duration that is longer than T_{UP} (Fig. 2), the equipment can be shut down or disconnected from the supply; consequently, the process parameter starts to deviate from its normal value. This paper considers that this deviation is instantaneous, that is, the "dead time" in the process response is not considered [11]. Due to an uncertainty in the voltage tolerance curve of the equipment, the start point of deviation may be between T_{UP} and T_{LW}. If this variation continues after the process variable threshold P_{limit}, the normal operation of the process cannot be preserved. Fig. 2 shows two time values $T_{\mathrm{UP}}^{\mathrm{P}}$ and $T_{\mathrm{LW}}^{\mathrm{P}}$, when the process failure/trip may occur. It is assumed, for illustrative purposes only, that for a V_{sag}, there is the same uncertainty region between T_{UP} and T_{LW} as between $T_{\mathrm{UP}}^{\mathrm{P}}$ and $T_{\mathrm{LW}}^{\mathrm{P}}$. Thus, $T_{\mathrm{UP}}^{\mathrm{P}} = T_{\mathrm{UP}} + PIT$ and $T_{\mathrm{LW}}^{\mathrm{P}} = T_{\mathrm{LW}} + PIT$. In the general case, these two regions can be different though. After the critical process variable crosses the P_{limit} at a time between $T_{\mathrm{UP}}^{\mathrm{P}}$ and $T_{\mathrm{LW}}^{\mathrm{P}}$, the process can no longer operate as intended and must be shut down, or restarted, or otherwise corrected. It is important to note that the equipment will trip onwards from point T_{UP}, while the process will trip only after point $T_{\mathrm{UP}}^{\mathrm{P}}$. This observation considers that equipment, before $T_{\mathrm{UP}}^{\mathrm{P}}$ can be restarted after a sag or short duration interruption event. In some cases, this restart cannot be achieved either because the equipment does not have an autoreset (reclosing) option or the PIT is too short (typically 2–4 s [11]). The equipment without autoreset cannot be automatically restarted after the voltage recovers to its normal value so the process may not ride-through. A correction factor can be used to include these cases as discussed in the sequel.

A. Derivation of Cumulative Probability Curves of Power-Supply Interruption Duration

Using a CPSD, it is possible to obtain P_{sag} and P_{LDI}. However, in order to analyze how an LDI affects equipment and processes, it is important to know how long a customer is going to be without the electricity supply after the fault. This duration includes fault location time, repair time, etc. This curve is referred to as the cumulative probability curve of power supply interruption duration (CSID). It can be obtained using historical data and can be different for customers located in different protection areas. For a representative time T, CSID can provide the cumulative probability value of power supply interruption duration $(P_{\mathrm{SID}}(T))$ for the instant T.

B. Different Cases of Process Trip

Following the criteria presented before, the evaluation of process trip probability due to sags and LDI is described for two characteristic cases. In both cases, it is assumed that the PIT is long enough (i.e., equipment trip does not instantaneously leads to process trip) and that the equipment can always be restarted after a sag. This assumption will be adjusted later using a correction factor.

Case 1: Process trip due to LDI (Zn1).

Consider a sensitive device in the customer's facility with a representative sensitivity curve as shown in Fig. 2 and two fault conditions (C_{N1} and C_{N2}) which affect a representative process. C_{N1} and C_{N2} cause two different sags (V_{sag1} and V_{sag2}) and two different protection times (T_{I1} and T_{I2}). For C_{N1}, as $T_{I1} < T_{\mathrm{UP}}$, this condition does not affect the uncertainty region of the customer's equipment. In T_{I1}, customers downstream of the protection device are exposed to energy supply interruption. For C_{N1}, due to the lack of energy supply, the process parameter starts decreasing after T_{I1}. However, the process trip starts only after $T_{\mathrm{UP1}}^{\mathrm{P}} = T_{I1} + \mathrm{PIT}$. The C_{N2} is similar to C_{N1}, but with $V_{\mathrm{sag2}} > V_{\mathrm{UP}}$, in other words, equipment is not affected by sags. The process trip in this case starts after $T_{\mathrm{UP2}}^{\mathrm{P}} = T_{I2} + \mathrm{PIT}$.

In order to estimate process trip probability, the trips are counted only in the zone $Zn1$ between $T_{\mathrm{UP1}}^{\mathrm{P}}$ and T_∞ for C_{N1} and between $T_{\mathrm{UP2}}^{\mathrm{P}}$ and T_∞ for C_{N2}, where $T_\infty = 24$ h.

Since for both conditions, the sensitivity curve is not affected, that is, the losses caused by sags are not considered, $Zn1$ can be calculated by the following equation:

$$\begin{aligned} &Zn1(\mathrm{PIT}, T_{Ib}) \\ &\quad = \left\lfloor P_{\mathrm{SID}}(T_\infty - T_{Ib}) - P_{\mathrm{SID}}\left(T_{\mathrm{UPb}}^{\mathrm{P}} - T_{Ib}\right)\right\rfloor \times P_{\mathrm{LDI}}(T_{Ib}) \end{aligned} \tag{5}$$

where b is type of condition for case 1 ($b = 1$ for C_{N1} and $b = 2$ for C_{N2}). T_{Ib} and $T_{\mathrm{UPb}}^{\mathrm{P}}$ are the protection time and the beginning of process trip, respectively, for the index b. In (5), as $P_{\mathrm{SID}}(T)$ considers only events starting from the moment of energy interruption, it is necessary to discount T_{Ib} to T_∞ and $T_{\mathrm{UPb}}^{\mathrm{P}}$ in order to use correctly CSID.

Since $T_{\mathrm{UPb}}^{\mathrm{P}} = T_{Ib} + \mathrm{PIT}$ and $T_\infty \ggg T_{Ib}$, then (5) can be reduced to

$$Zn1(\mathrm{PIT}, T_{Ib}) = [P_{\mathrm{SID}}(T_\infty) - P_{\mathrm{SID}}(\mathrm{PIT})] \times P_{\mathrm{LDI}}(T_{Ib}). \tag{6}$$

Case 2: Process trip due to sag and LDI (Zn1, Zn2, and Zn3)

This case also considers two situations:

- First; $V_{\mathrm{sag}} < V_{\mathrm{UP}}, T_I > T_{\mathrm{UP}}$ and $\mathrm{PIT} \leq T_I - T_{\mathrm{UP}}$. Those restrictions produce two new zones $Zn2$ and $Zn3$ as the result of the uncertainty in sensitivity curve (see Fig. 3). $Zn3$ starts between $T_{\mathrm{UP}}^{\mathrm{P}}$ and T_I; $Zn2$ starts between T_I and T_I^{P}; and $Zn1$ starts between T_I^{P} and T_∞. The process trip starts only after $T_{\mathrm{UP}}^{\mathrm{P}} = T_{\mathrm{UP}} + \mathrm{PIT}$. The variables $Zn1$, $Zn2$, and $Zn3$ are calculated in (6)–(8) respectively

$$\begin{aligned} Zn2(\mathrm{PIT}, V_{\mathrm{sag}}, T_I) = &\sum_{r=0}^{nr-1} \left[\left(P_{\mathrm{SID}}\left(T_{2(r+1)}^{\mathrm{P}} - T_I\right)\right.\right. \\ &\left. - P_{\mathrm{SID}}\left(T_{2(r)}^{\mathrm{P}} - T_I\right)\right) \\ &\left. \times Un_{\mathrm{PT}}\left(T_{2(r)}^{\mathrm{P}} - \mathrm{PIT}, V_{\mathrm{sag}}\right)\right] \\ &\times xP_{\mathrm{LDI}}(T_I) \\ nr = Integer &\left[\frac{(T_I^{\mathrm{P}} - T_I)}{\delta}\right]; \\ T_{2(r+1)}^{\mathrm{P}} = T_{2(r)}^{\mathrm{P}} &+ \delta; \quad T_{2(0)}^{\mathrm{P}} = T_I \end{aligned} \tag{7}$$

$$\begin{aligned} Zn3(PIT, V_{\mathrm{sag}}) = &\sum_{k=0}^{nk-1} \left[\left(P_{\mathrm{sag}}\left(T_{3(k+1)}^{\mathrm{P}}\right) - P_{\mathrm{sag}}\left(T_{3(k)}^{\mathrm{P}}\right)\right)\right. \\ &\left. \times Un_{\mathrm{PT}}\left(T_{3(k)}^{\mathrm{P}} - \mathrm{PIT}, V_{\mathrm{sag}}\right)\right] \\ nk = Integer &\left[\frac{(T_I - T_{\mathrm{UP}}^{\mathrm{P}})}{\delta}\right]; \\ T_{3(k+1)}^{\mathrm{P}} = T_{3(k)}^{\mathrm{P}} &+ \delta; \quad T_{3(0)}^{\mathrm{P}} = T_{\mathrm{UP}}^{\mathrm{P}}. \end{aligned} \tag{8}$$

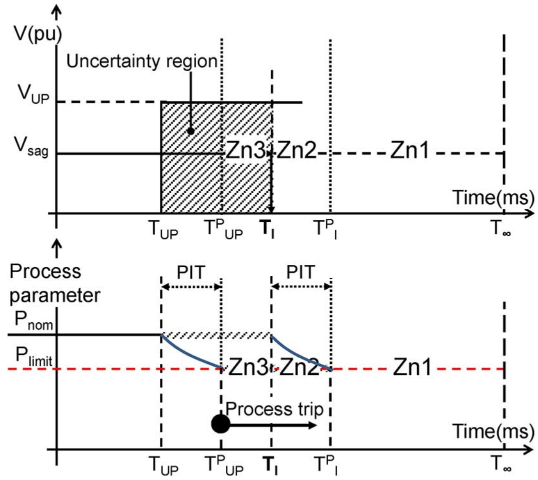

Fig. 3. Case 2—a process trip is caused by sag and LDI.

where r and nr are index of points and the number of points between T_I and T_I^{P}, respectively, for the zone $Zn2$; k and nk are the index of points and the number of points between $T_{\mathrm{UP}}^{\mathrm{P}}$ and T_I, respectively, for the zone $Zn3$. $T_{2(r)}^{\mathrm{P}}$ is the time value for index r for zone $Zn2$. $T_{3(k)}^{\mathrm{P}}$ is time value for index k for zone $Zn3$; $\delta \approx$10 ms [7]. In (7) and (8), as $Un_{\mathrm{PT}}(T, V)$ is calculated using T_{UP} as a reference, it is necessary to remove PIT for each value of $T_{2(r)}^{\mathrm{P}}$ and $T_{3(k)}^{\mathrm{P}}$ in order to correctly use (3). Thus, the whole probability value is calculated as $Zn1 + Zn2 + Zn3$.

- Second: $V_{\mathrm{sag}} < V_{\mathrm{UP}}, T_I > T_{\mathrm{UP}}$ and $\mathrm{PIT} > T_I - T_{\mathrm{UP}}$. In this case, zone $Zn3 = 0$. If sensitivity curves among T_{UP}, T_I and V_{UP} have the same decay time constant, the zone $Zn2$, for a defined PIT, starts between $T_{\mathrm{UP}}^{\mathrm{P}} = T_{\mathrm{UP}} + \mathrm{PIT}$ and $T_I^{\mathrm{P}} = T_I + \mathrm{PIT}$. The zone $Zn1$ represents only the LDI effect and it starts between T_I^{P} and T_∞. Thus, for that second situation, the process trip starts after $T_{\mathrm{UP}}^{\mathrm{P}}$.

Considering the aforementioned derivations for each simulated short circuit, the values of V_{sag} and T_I can be used together with the sensitivity curve to define which case should be used in the assessment of probability of the process trip.

For a defined PIT value, the probability of process trip related to sag ($P_{\mathrm{PTS}}(\mathrm{PIT})$) and LDI ($P_{\mathrm{PTL}}(\mathrm{PI})$) can now separately be obtained using $Zn1$, $Zn2$, and $Zn3$ as shown by (9) and (10). And the Total ($P_{\mathrm{PTT}}(\mathrm{PIT})$) by

$$P_{\mathrm{PTS}}(\mathrm{PIT}) = Zn2 + Zn3 \tag{9}$$

$$P_{\mathrm{PTL}}(\mathrm{PIT}) = Zn1 \tag{10}$$

$$P_{\mathrm{PTT}}(\mathrm{PIT}) = P_{\mathrm{PTS}}(\mathrm{PIT}) + \mathrm{P}_{\mathrm{PTL}}(\mathrm{PIT}). \tag{11}$$

C. Correction Factor for the Equipment Restart Condition

A sag may disturb the normal function of equipment and cause the interruption of the entire process. For this case, the process will not trip if the nominal voltage is recovered before its PIT. However, for that to occur, the equipment has to be restarted as well. If there is no auto-reset (reclosing) for the equipment or, even when there is one, but it may fail when voltage recovers, the equipment and the process will not be reconnected to the supply. For that case, the process will trip even when its PIT is long enough to support a perturbation. In order to consider the existence of auto-reset in equipment, a factor for equipment restart (F_{ERS}) is introduced in (12). The boundary of 4 s is suggested in [11].

$$F_{\mathrm{ERS}} = \begin{cases} 1 & \mathrm{PIT} \leq 4\ \mathrm{s} \\ \frac{1}{20} & \mathrm{PIT} > 4\ \mathrm{s} \end{cases}. \tag{12}$$

Equation (12) considers that for low values of PIT, for example, 4 s, equipment cannot be reset to recover its normal operation. Thus, if PIT $\leq$4 s, an equipment trip always yields a process trip. On the other hand, if PIT $>$4 s, equipment can be automatically or manually reset and the process trip will start after PIT (T_{UP}^{P} of Fig. 3). For illustrative purposes, it is assumed that only in one of 20 events, the equipment could not be reset after the voltage supply recovers to its nominal value. Therefore, only one-twentieth of the process immunity area between T_{UP} and $T_{\mathrm{UP}}^{\mathrm{P}}$ (Fig. 3) has to be considered during the evaluation of the process trip probability. To increase the accuracy of F_{ERS}, it is necessary to know the relationship between equipment capacity to restart and PIT of the processes. Although this paper uses two values for F_{ERS}, different F_{ERS} for different types of processes or for different types of customers can be considered if the information is available. For this, however, very detailed analysis of equipment and process behavior is essential.

Applying F_{ERS} in (11) new formulations are obtained for the two cases introduced in Section III-B.

Case 1:

$$P_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT}) = 0.0 \tag{13}$$

$$P_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT}) = P_{\mathrm{PTL}}(\mathrm{PIT}) + [\mathrm{P}_{\mathrm{PTL}}(0) - \mathrm{P}_{\mathrm{PTL}}(\mathrm{PIT})] \times F_{\mathrm{ERS}}. \tag{14}$$

Case 2:

$$P_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT}) = P_{\mathrm{PTS}}(\mathrm{PIT}) + \mathrm{Z}_{\mathrm{PTS}} \times \mathrm{F}_{\mathrm{ERS}}$$

$$Z_{\mathrm{PTS}} = [P_{\mathrm{PTS}}(0) + P_{\mathrm{PTL}}(0)] - [P_{\mathrm{PTS}}(\mathrm{PIT}) + \mathrm{P}_{\mathrm{PTL}}(\mathrm{PIT})] \tag{15}$$

$$P_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT}) = P_{\mathrm{PTL}}(\mathrm{PIT}) \tag{16}$$

where $P_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT})$ and $P_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT})$ are the probability of process trip due to sag and LDI considering the restart factor. Thus, for a defined PIT, the overall probability of process trip ($P_{\mathrm{PTT}}^{\mathrm{RS}}(\mathrm{PIT})$) is given by

$$P_{\mathrm{PTT}}^{\mathrm{RS}}(\mathrm{PIT}) = \mathrm{P}_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT}) + \mathrm{P}_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT}). \tag{17}$$

D. Probability Distribution of PIT

In order to determine the PIT value, it is important to know the interconnection between "equipment and parameter" for each process or subprocess [12]. For an existing process, historical information as disturbances and their effects on the process can be used. For new processes, simulation or experience from similar processes can be a helpful tool. Nevertheless, it is possible to draw a probability distribution curve which represents its behavior. For illustrative purposes, one representative curve, using $\mu = 1$ min and $\sigma = 3$ min can be designed. For that curve, the probabilistic values of PIT can be interpreted as follows: there is 40.1% probability that processes have PIT $= 0$ min;

53.3% probability that PIT < 1 min and; 99.8% probability that PIT < 10 min.

Using the probability distribution for PIT, a procedure can be structured to obtain the average values of process trip probability considering the restart condition ($\mathrm{AP}_{\mathrm{PTT}}^{\mathrm{RS}}(\mathrm{PIT})$) due to both (sag and LDI). The procedure is described by the following steps:

Step 1) initialize $\mathrm{Tot}_{\mathrm{PTS}} = 0$; $\mathrm{Tot}_{\mathrm{PTL}} = 0$; and $\mathrm{Tot}_{\mathrm{PTT}} = 0$;

Step 2) calculate random value (t) between 0 and 1;

Step 3) for j, a PIT_t is obtained using the cumulative probability distribution for process immunity time;

Step 4) for PIT_t, $P_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT}_t)$, $P_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT}_t)$, and $P_{\mathrm{PTT}}^{\mathrm{RS}}(\mathrm{PIT}_t)$ are calculated using (13)–(17);

Step 5) assess

$$\begin{aligned}\mathrm{Tot}_{\mathrm{PTS}} &= \mathrm{Tot}_{\mathrm{PTS}} + P_{\mathrm{PTS}}^{\mathrm{RS}}(\mathrm{PIT}_t)\\ \mathrm{Tot}_{\mathrm{PTL}} &= \mathrm{Tot}_{\mathrm{PTL}} + P_{\mathrm{PTL}}^{\mathrm{RS}}(\mathrm{PIT}_t)\\ \mathrm{Tot}_{\mathrm{PTT}} &= \mathrm{Tot}_{\mathrm{PTT}} + P_{\mathrm{PTT}}^{\mathrm{RS}}(\mathrm{PIT}_t);\end{aligned}$$

Step 6) check whether N_t random values are sorted. If yes, go to Step 7); if not, go to Step 2). A suggested value for N_t is 1000;

Step 7) to calculate the average value for different probabilities

$$\begin{aligned}\mathrm{AP}_{\mathrm{PTS}}^{\mathrm{RS}} &= \frac{\mathrm{Tot}_{\mathrm{PTS}}}{N_t}\\ \mathrm{AP}_{\mathrm{PTL}}^{\mathrm{RS}} &= \frac{\mathrm{Tot}_{\mathrm{PTL}}}{N_t}\\ \mathrm{AP}_{\mathrm{PTT}}^{\mathrm{RS}} &= \frac{\mathrm{Tot}_{\mathrm{PTT}}}{N_t}.\end{aligned} \tag{18}$$

E. Correction Factor for Protection Reliability

The method proposed in [5] considers that the protection device closest to the fault location on the path to the substation is always the one to actuate and isolate a minimum number of customers. However, the method proposed in [5] can be improved by taking into account the reliability of upstream protection devices, as suggested in [16].

A new correction factor, referred to as factor-reliability (F_{RB}) is therefore used in this study to consider the possibility of protection device failure when it is exposed to a short-circuit current. In this situation, other upstream protection devices may be activated to isolate this short circuit. The evaluation of F_{RB} for each protection device is obtained as a function of fault location, protection areas, and failure rate (λ, a real value between 0 and 1).

Consider a network with three protection devices PD1, PD2, and PD3 (PD1 is near the substation and PD3 is far away from the substation) which creates three protection areas $Z1$, $Z2$, and $Z3$, and three customer C1, C2, and C3, one in each area, respectively. For a fault in $Z3$, the F_{RB} value, per customer, is obtained as follows:

Area 1) customer C1 $=> \mathrm{F_{RB}} = (1-\lambda_1)\mathrm{x}\lambda_2\mathrm{x}\lambda_3$.
Area 2) customer C2 $=> \mathrm{F_{RB}} = (1-\lambda_2)\mathrm{x}\lambda_3$.
Area 3) customer C3 $=> \mathrm{F_{RB}} = (1-\lambda_3)$.

Based on this and considering a short circuit in zone 3: For PD3 with $\lambda_3 = 0$, this protection device always looks after customer downstream of PD3. For PD3 with $\lambda_3 = 1$, this protection device always fails; consequently, the next protection device PD2 may look after the customer downstream of PD2 and PD3.

F. Correction Factor for the Type of Fault

This factor (F_{TF}) considers the possibility of symmetrical or asymmetrical faults that may occur at different phases from those that a customer (single phase, two phase, or three phase) is connected to. For example, a phase-to-ground fault can affect any phases A, B, or C; consequently, the probability of this fault occurring and affecting a single-phase customer is 1/3. Different values of F_{TF}, for different types of customers (single or three phase connected) and different type of faults, can be used: 1) single-phase customer: phase to ground $F_{\mathrm{TF}} = 1/3$, phase to phase and phase to phase to ground $F_{\mathrm{TF}} = 2/3$, and three phase $F_{\mathrm{TF}} = 1.0$; 2) two-phase customer: phase to ground $F_{\mathrm{TF}} = 2/3$, phase to phase, phase to phase to ground and three phase $F_{\mathrm{TF}} = 1.0$; and 3) three-phase customers: all types of faults $F_{\mathrm{TF}} = 1.0$.

IV. Calculating an Annual Number of Process Trips

Using (18), one can calculate $\mathrm{AP}_{\mathrm{PTS}}^{\mathrm{RS}}$, $\mathrm{AP}_{\mathrm{PTL}}^{\mathrm{RS}}$, and $\mathrm{AP}_{\mathrm{PTT}}^{\mathrm{RS}}$ for one fault at a time. A large number of faults occurring throughout the network need to be simulated and integrated in calculation in order to estimate the annual number of process trips as shown

$$N_{prot} = \sum_{n=1}^{N}\sum_{d=1}^{Nd}\left(P_{\mathrm{LDI}}^{d,n} \times F_{\mathrm{RB}}^{d} \times F_{\mathrm{TF}}^{n}\right) \tag{19}$$

$$N_{\mathrm{years}} = \frac{N_{\mathrm{prot}}}{(\lambda_{\mathrm{DF}} \times d_{\mathrm{DF}})} \tag{20}$$

$$\begin{aligned}\mathrm{NPT}_{\mathrm{sag-year}}^{c} &= \frac{\sum_{n=1}^{N}\sum_{d=1}^{Nd}\left(\left(\mathrm{AP}_{\mathrm{PTS}}^{\mathrm{RS}}\right)_{d,n} \times F_{\mathrm{RB}}^{d} \times F_{\mathrm{TF}}^{n}\right)}{N_{\mathrm{years}}}\\ \mathrm{NPT}_{\mathrm{LDI-year}}^{c} &= \frac{\sum_{n=1}^{N}\sum_{d=1}^{Nd}\left(\left(\mathrm{AP}_{\mathrm{PTL}}^{\mathrm{RS}}\right)_{d,n} \times F_{\mathrm{RB}}^{d} \times F_{\mathrm{TF}}^{n}\right)}{N_{\mathrm{years}}}\end{aligned} \tag{21}$$

$$\mathrm{NPT}_{\mathrm{Tot-year}}^{c} = \mathrm{NPT}_{\mathrm{sag-year}}^{c} + \mathrm{NPT}_{\mathrm{LDI-year}}^{c} \tag{22}$$

where d, n, and c are indices of protection devices activated to isolate the fault, number of faults, and number of customers, respectively. Nd is a set of protection devices between the fault position and substation following the path of fault current. N is the total number of faults. N_{years} and N_{prot} are the total number of years and total number of simulations where protection devices are activated, respectively. d_{DF} is the feeder length in kilometers (given as sum of the main and lateral branches), λ_{DF} is the annual fault occurrence rate per kilometer on a feeder. $\mathrm{NPT}_{\mathrm{sag-year}}^{c}$, $\mathrm{NPT}_{\mathrm{LDI-year}}^{c}$, and $\mathrm{NPT}_{\mathrm{Tot-year}}^{c}$ are the annual number of process trips due to sag, LDI, and both together, respectively, for customer c.

TABLE I
PROBABILITY OF PROCESS RESTART

Re-start process time T_{PRS} (hours)	$Prob_{PRS}(T_{PRS})$
$0 \leq T_{PRS} \leq 1$	0.6
$1 < T_{PRS} \leq 4$	0.3
$4 < T_{PRS} \leq 24$	0.1

V. Methodology for the Assessment of Financial Losses

The assessment of financial losses incurred by the customer due to process interruption is performed in two steps. The first is a set of different process configurations, adopted from [15]. These configurations include series/parallel connection among four common types of sensitive equipment—ac contactors, PC, PLC, and ASD. These processes are randomly assigned to all customers, creating a link "process-customer."

The second step is a correlation between the time required for the process to restart its regular operation (T_{PRS}) and probability of process restart $P_{\mathrm{PRS}}(T_{\mathrm{PRS}})$—manual or automatic. The cumulative probability curve of process restart (CPRS) can be obtained using historical reports about similar events (for example, Table I).

The customer interruption costs (CICs) for different categories are adopted from [15]. To improve the accuracy of the economic assessment, a factor of customer activity (FCA)—of various customer types—is also considered. These values are adopted from [15].

A. Financial Losses Due to Sag

By correlating $P_{\mathrm{PRS}}(T_{\mathrm{PRS}})$, CIC, and FCA with $\mathrm{NPT}^{c}_{\mathrm{sag-year}}$, it is possible to calculate the annual financial losses related to process trip due to sag for each customer ($\mathrm{FLPT}^{c}_{\mathrm{sag-year}}$) as shown by (23).

$$\mathrm{FLPT}^{c}_{\mathrm{sag-year}} = \sum_{h=1}^{H} \left(P_{\mathrm{PRS}}(\mathrm{TPRS}_{h}) \times \mathrm{CIC}^{c}_{h} \times \mathrm{FCA}^{c} \times \mathrm{NPT}^{c}_{\mathrm{sag-year}}\right) \quad (23)$$

where h is time of process restart and H is the total number of time of process restarts.

B. Financial Losses Due to LDI

In order to assess the annual financial losses related to process trip due to LDI ($\mathrm{FLPT}^{c}_{\mathrm{LDI-year}}$), it is necessary to know the time of the process interruption (T_{TPI}), that is, from the instant of loss of power supply until the process recovers from its normal operation. Thus, T_{TPI} can be evaluated as the sum of the duration of the interruption of energy supply (T_{IES}) and T_{PRS}. The criterion considered in this study assumes that after an LDI, the procedure for restarting a process can start only after the supply voltage is fully restored. Obviously, this is a simplification, since the restart procedure can begin before or after the voltage fully recovers. Modification of this criterion can be easily introduced without affecting the proposed methodology. The calculated numerical values might be slightly different though. However, in light of all other uncertainties considered, even that effect (slightly different numerical values) would not be significant. The variable $\mathrm{FLPT}^{c}_{\mathrm{LDI-year}}$ is obtained in an iterative procedure as follows:

- Step 1) for a customer c;
- Step 2) iteration z, calculate a random value between 0 and 1 to obtain $T_{\mathrm{PRS-z}}$ by using probabilistic values of CPRS;
- Step 3) iteration z, calculate a random value between 0 and 1 to obtain $T_{\mathrm{RNS-z}}$ using probabilistic values of CSID (see Section III-A);
- Step 4) calculate
$$T_{\mathrm{TPL-z}} = T_{\mathrm{PRS-z}} + T_{\mathrm{IES-z}} \text{ and } \mathrm{CIC}^{c}_{\mathrm{Total}} = \mathrm{CIC}^{c}_{\mathrm{Total}} + \mathrm{CIC}^{c}_{z}(T_{\mathrm{TPI-z}});$$
- Step 5) check whether N_{ite} random values are sorted. If yes, go to Step 6); if not, go to Step 2). A recommended value for N_{ite} is 10 000;
- Step 6) calculate $\mathrm{FLPT}^{c}_{\mathrm{PTL-year}}$:

$$\mathrm{FLPT}^{c}_{\mathrm{LDI-year}} = \frac{\mathrm{CIC}_{\mathrm{Total}}}{\mathrm{Nite}} \times \mathrm{NPT}^{c}_{\mathrm{LDI-year}} \times \mathrm{FCA}^{c}. \quad (24)$$

The total financial losses related to the process trip for a customer c ($\mathrm{TFLPT}^{c}_{\mathrm{year}}$) are calculated by

$$\mathrm{TFLPT}^{c}_{\mathrm{year}} = \mathrm{FLPT}^{c}_{\mathrm{sag-year}} + \mathrm{FLPT}^{c}_{\mathrm{LDI-year}}. \quad (25)$$

Finally, the annual financial losses for the entire network ($\mathrm{NetworkFLPT}_{\mathrm{year}}$) can be estimated by summing up the financial losses of each customer as shown in (26), where nc is the total number of customers in the network.

$$\mathrm{NetworkFLPT}_{\mathrm{year}} = \sum_{c=1}^{nc} \mathrm{TFLPT}^{c}_{\mathrm{year}}. \quad (26)$$

VI. Application to the Real Distribution Network

In order to illustrate the proposed methodology, a real distribution network is used as shown in Fig. 5. This network is formed by a 27.4-km distribution line, 1311 buses, and 186 consumers (74 residential, 41 commercial, 54 industrial, and 17 large customers). The fault occurrence rate is 1 fault/km/yr. A set of 1000 faults is simulated using the Hybrid method proposed in [5]. All simulations are carried out using the SINAPgrid Platform [17] on a PC with a CPU Intel Core i7 2.9 GHz–6 GB RAM.

For the illustration of methodology, six process types shown in Fig. 4 are used. Each type of process uses one of the available types of sensitive equipment: ac contactors, PLC, PC, and ASD. Their sensitivity curves considering uncertainty areas are adopted from [15] (high sensitivity is considerate in order to analyze the worst scenario). These processes are randomly assigned to customers in the network in order to assess their annual process trip. The number of customers per process types, from Fig. 4, being arbitrarily assigned is Type I = 27, Type II = 38, Type III = 24, Type IV = 27, Type V = 36, and Type VI = 34. The CPRS used is shown in Table I.

The CSID used is called de normal-CSID. For that curve, 100% of LDIs can be repaired within 16 h; 95% of LDIs can be repaired within 8 h and 70% of LDIs can be repaired within 2 h. The factor $\mathrm{F}_{\mathrm{RB}} = 0$.

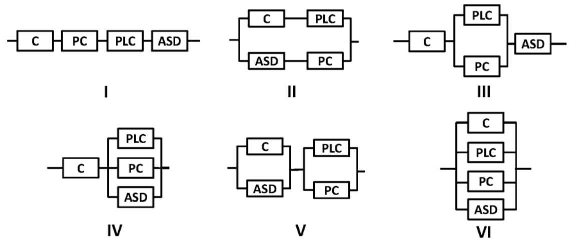

Fig. 4. Six process configuration used during the financial loss assessment on customers.

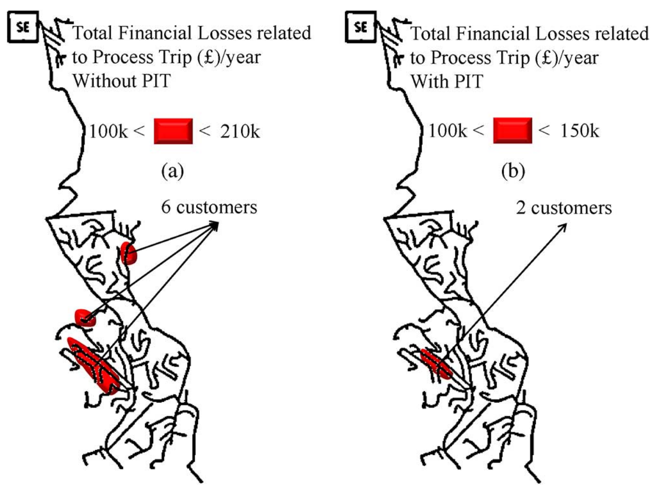

Fig. 5. Geographic areas identifying a set of affected customers. Annual financial losses related to process trip: (a) without PIT and (b) with PIT.

Fig. 5 shows different geographic areas in the network with groups of customers that are more affected by annual financial losses related to process trip. In Fig. 5(a), without PIT, three regions are highlighted. Six customers located in these regions have the highest annual values of financial losses. The financial losses in these three regions (and, consequently, the size of these regions) are still overestimated because they do not consider PIT. In fact, as shown in Fig. 5(b), the region obtained with PIT is reduced in comparison with Fig. 5(a). Therefore, this new region (comprising only two customers) should be the one to be considered by utilities to start corrective action or discussion with customers in order to reduce the financial losses and dissatisfaction of the customers located in that region.

Table II shows financial losses due to sag and LDI with and without PIT for the entire network. It can be seen that there is a 56% reduction of annual financial losses due to sags from £887 K without PIT to £391 K with PIT. This reduction is caused by the probability distribution of PIT used for the proposed methodology. Thus, with PIT taken into account, financial losses due to sags represent 34% of financial losses due to LDI and 25% of all financial losses. It can be also seen from Table II that the inclusion of PIT impacts mainly financial losses due to sags because with inclusion of PIT in assessment only a fraction of events, which affect customer's equipment, affect customer's processes as well. Without PIT, the value of annual financial losses for the entire network is approximately £2.0 M, but with PIT, this value is reduced to approximately £1.5 M, in other words, a reduction of £500 K or 25%.

TABLE II
COMPARISON WITH AND WITHOUT PIT FOR THE ENTIRE NETWORK

Due to	Total financial losses(£/year)	
	Without PIT	With PIT
sag	887,987	391,106
LDI	1,151,583	1,136,706
Total	2,039,570	1,527,812

VII. CONCLUSION

This paper introduced a comprehensive probabilistic methodology to assess annual financial losses due to voltage sags and long duration interruptions to individual customers and the distribution network as a whole. Furthermore, the methodology incorporates for the first time recently defined process immunity time in the assessment of financial losses due to fault-induced process interruptions. By inclusion of PIT in the assessment, the methodology facilitates a more realistic assessment of annual financial losses due to process interruption.

For all cases studied, the financial losses with PIT included are lower than financial losses without PIT. This reduction is dependent on the immunity of the process to voltage sag and LDI. Some faults and resulting voltage sags can affect the equipment and process. However, only PIT can define which of these events can cause financial losses to customers. The process with the highest PIT values (longest duration) experiences the lowest financial losses. Therefore, PIT is an essential parameter for designing resilient industrial/commercial processes.

The proposed methodology can be directly used by network operators and individual customers to estimate potential financial losses in their plants/networks and to develop appropriate mitigation measures. At the network level, appropriate planning measures can be undertaken in order to enhance the overall quality of services to customers and meet increasing regulatory demands.

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