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A novel methodology for determining the voltage sag Impact Factor

Marcos V. Costa[a,*], José M.C. Filho[a], Roberto C. Leborgne[b], Natanael B. Pereira[c]

[a] Universidade Federal de Itajubá, Av. BPS, 1303, Itajubá, MG, 37500-903, Brazil
[b] Universidade Federal do Rio Grande do Sul, Av. Osvaldo Aranha, 103, Porto Alegre, RS, 90035-190, Brazil
[c] Energias de Portugal, R. Claudino Pinto, 58, São José dos Campos, SP, 12210-010, Brazil

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ABSTRACT

This paper proposes a methodology for determining a site index that considers the equipment sensitivity to voltage sags, the variation in their level of sensitivity, and the influence of unbalanced sags on three-phase loads. Some single-event characteristics are easily applicable when obtaining site indexes, however, they are overly generic to consider all the above-mentioned aspects, and the more specific indices present the inconvenience of calculation parameters that are dependent on the equipment type, which makes them more adequate to quantify the impact of voltage sags on certain loads rather than to evaluate the sites' performance. In this context, the proposed methodology aims to obtain a single set of calculation parameters that is applicable to all cases, allowing large-scale assessments. For this purpose, a statistical approach is adopted, considering the correlation between the index and the number of equipment trips, in order to define the adjustment most correlated with the sensitivity level of different types of loads. The Impact Factor is used as a basis in determining the desired index. A case study illustrates the application of the proposed methodology, showing how these aspects can be addressed from a better definition of the Impact Factor.

1. Introduction

With the modernization of industry and the electric sector deregulation, power quality (PQ) has become an increasingly relevant issue for both consumers and utilities [1,2]. Among PQ disturbances, voltage sags are one of the most critical problems. In certain industries, a sag event lasting only a few milliseconds can cause a prolonged interruption of processes, which may take several hours to be restarted, generating high financial losses due to downtime [3,4].

Nevertheless, despite the relevance of these phenomena, few countries in the world present criteria for their regulation [5]. In the case of Brazil, there have recently been great advances in this regard with the update of the Distribution Procedures (Prodist) Module 8 [6], and a new index called "Impact Factor" (*IF*) has been created. However, the way in which its calculation parameters were determined has not been clearly explained, raising several questions about their adequacy.

The IEEE Std. 1564 [7], in turn, provides methods to quantify the events severity and the performance of sites and systems. The site indexes are calculated from the single-event characteristics, such as the voltage sag energy (Evs) or the voltage sag severity (Se), of all events measured in a given period of time, and the system indexes are calculated from the site indexes. Besides Evs and Se [7], a number of other single-event characteristics have also been proposed in the literature, such as the sag score [8], the lost energy (W) [9], the missing voltage time area (MVTA) [10], the sag SAIFI [11], the magnitude duration severity index (MDSI) [12], and the sag severity index (SSI) [13]. However, although there are several indices, there is still no consensus on which ones should be used.

It is known that the severity of voltage sags is closely related to the response of sensitive loads [1,3], but Evs, sag score, W, and MVTA do not take the equipment sensitivity into account. On the other hand, Se, sag SAIFI, MDSI, and SSI are calculated based on voltage tolerance curves. Generally, CBEMA, ITIC, or SEMI F47 standards are used, which aim to approximate the response of certain equipment or processes to voltage sags and, therefore, they are not applicable in all cases, given the large variation in equipment's sensitivity, even among those of the same type. The MSDI and SSI indexes allow to incorporate the uncertainty involved in load response, however, their calculation parameters are dependent on the equipment type, making it difficult to use them in obtaining site indexes, since it would be necessary to calculate the index relative to each type of equipment under analysis. This could be further complicated when considering the influence of unbalanced sags [3,14,15] on three-phase loads.

In this context, this paper proposes a methodology for determining a

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[*] Corresponding author.

E-mail addresses: marcosvcost@gmail.com (M.V. Costa), jmaria@unifei.edu.br (J.M.C. Filho), roberto.leborgne@ufrgs.br (R.C. Leborgne), natanael.pereira@edpbr.com.br (N.B. Pereira).

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site index that considers all these aspects in a rational and intuitive way. Firstly, the events are weighted proportionally to the trip probability of the loads. The adjustment of the calculation parameters is carried out by evaluating the correlation between the index and the estimated number of equipment trips, in order to define a single set of calculation parameters that reflects the sensitivity level of different types of loads and allows obtaining the site's index directly. The proposed methodology is applied based on the Impact Factor, also seeking to fill the existing gap in the definition of this index, as mentioned before.

This paper is organized as follows: Section 2 introduces the Impact Factor according to Prodist Module 8. The proposed methodology for determining its calculation parameters is presented in Section 3. Section 4 presents a case study illustrating the application of the proposed methodology and the obtained results. Section 5 presents the conclusions.

2. Impact Factor

With the update of Prodist Module 8 in 2017, the Brazilian Electricity Regulatory Agency (ANEEL) defined that the sites' performance in Brazil, at 1 kV to 230 kV, should be evaluated by means of the Impact Factor. For the calculation of this index, the events recorded at the monitoring site must first be accounted for according to the classes defined in Table 1, considering a period of one month. Table 2 shows the categories formed from grouping the classes with the same weight, which were called "regions of sensitivity".

Thus, the Impact Factor (*IF*) is calculated by Eq. (1) [6].

$$IF = \frac{\sum_{i=A}^{I} ne_i .\ wf_i}{IF_{BASE}} \tag{1}$$

where ne_i is the number of events recorded in the region of sensitivity i in the reference month, wf_i is the respective weighting factor, and IF_{BASE} is the Base Impact Factor.

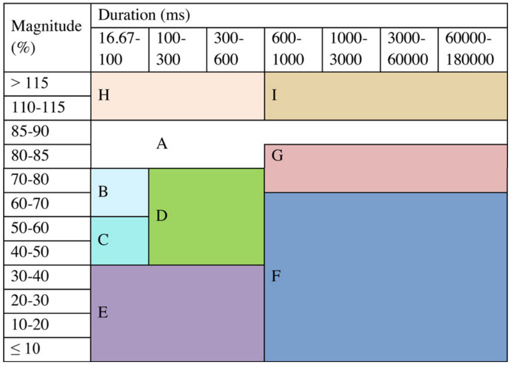
Table 3 indicates the weighting factor assigned to each region of sensitivity and the IF_{BASE} values defined for voltage levels from 1 kV to 69 kV and from 69 kV to 230 kV.

As stated in Prodist, the weighting factors were defined according to the importance of each event on the operation of loads, that is, larger weights were assigned to the regions of sensitivity considered as more impacting. The IF_{BASE} values, in turn, were defined from the sum of the products of these weights by the frequency of events shown in Table 4. Note that these frequencies are used only as reference in obtaining IF_{BASE}, not as limits. Thus, to evaluate the sites' performance, a reference value of 1 pu was set for the *IF* index.

Due to its regulatory impact, the updates proposed by ANEEL were submitted for discussion with society through two public consultations before coming into effect. Regarding the Impact Factor, most questions were about the definition of its calculation parameters, since the regulatory agency did not provide any details on this.

Therefore, this paper also aims to contribute to the consolidation of

Table 2
Regions of sensitivity for the calculation of the Impact Factor [6].



Magnitude (%)	Duration (ms)						
	16.67-100	100-300	300-600	600-1000	1000-3000	3000-60000	60000-180000
> 115	H			I			
110-115							
85-90	A						
80-85				G			
70-80	B	D					
60-70				F			
50-60	C						
40-50							
30-40	E						
20-30							
10-20							
≤ 10							

Table 3
Weighting factors and Base Impact Factors [6].

Region of sensitivity	Weighting factor (*wf*)	Base Impact Factor (IF_{BASE})	
		1–69 (kV)	69–230 (kV)
A	0.00	2.13	1.42
B	0.04		
C	0.07		
D	0.15		
E	0.25		
F	0.36		
G	0.07		
H	0.02		
I	0.04		

Table 4
Frequencies of events used as reference in obtaining IF_{BASE}.

Region of sensitivity	Frequency of events	
	1–69 (kV)	69–230 (kV)
B	5	4
C	4	3
D	3	2
E	2	1
F	1	1
G	4	1
H	1	1
I	1	1

Table 1
Magnitude-duration table from Prodist Module 8 [6].

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
> 115							
110–115							
85–90							
80–85							
70–80							
60–70							
50–60							
40–50							
30–40							
20–30							
10–20							
≤10							

this index. Although only reference values are indicated, limits will eventually be defined with the establishment of possible penalties. Then, it is essential that its calculation parameters are determined in a systematic and transparent manner, not only because of its regulatory nature, but also because of its role in resolving conflicts between consumers and utilities.

3. Methodology for determining the Impact Factor calculation parameters

From the consumers' point of view, an ideal index would be one capable of reflecting as closely as possible the impact caused by voltage sags. That is, its value should be directly proportional to a variable that quantified the impact of these disturbances on consumers. Based on this, the proposed methodology performs the adjustment of the calculation parameters of the *IF* index considering the Pearson's correlation coefficient (r) between this index and the estimated number of trips (*ENT*) of some types of equipment.

The coefficient r varies between -1 and $+1$. Values close to $+1$ indicate that the variables are directly proportional, which means that an increase in the number of trips would be followed by an increase in the *IF* value almost in the same proportion.

The objective is to define a single set of calculation parameters, that is, the regions of sensitivity and respective weighting factors, which represents the response of different types of equipment to voltage sags. The correlation coefficient is used to compare distinct adjustments of parameters, helping to select one of them.

The steps of the proposed methodology are described in the following subsections. It is worth pointing out that only voltage sags are considered, and that the voltage swells evaluation is not within the scope of this paper. Although the Prodist encompasses both events in the same index, it is recommended that they be treated separately [7].

3.1. Input variables

The adjustment of the calculation parameters of the Impact Factor is performed based on its correlation with the estimated number of equipment trips. Such variables can be calculated from a voltage sag database containing the monitoring results of several sites over a considerable period of time. The number of trips is estimated using a probabilistic approach, which is described in Subsection 3.2. The *ENT* values should be calculated for each of the monitoring sites and on a monthly basis. Furthermore, in the case of three-phase equipment, some additional considerations are made, as described in Subsection 3.3.

3.2. Estimating the number of equipment trips

In order to quantify the impact of voltage sags on consumers, the number of equipment trips is estimated based on the method proposed in Ref. [16], which considers the variation in loads' response against these events.

One of the assumptions of this method is that the equipment sensitivity can be characterized by means of a rectangular voltage tolerance curve, as shown in Fig. 1. However, it is worth mentioning that some types of equipment may exhibit a non-rectangular curve, as there are other parameters that can affect their performance besides magnitude and duration, such as the phase angle jump, the phase unbalance or any transient oscillation occurring during the event [1]. The contactor is a typical example of a device whose sensitivity depends on the point-on-wave at the time of sag initiation [17,18].

In the case of a rectangular curve, it is assumed that events deeper than the specified magnitude threshold V_{CRIT} and longer than the specified duration threshold T_{CRIT} will cause the equipment trip or malfunction.

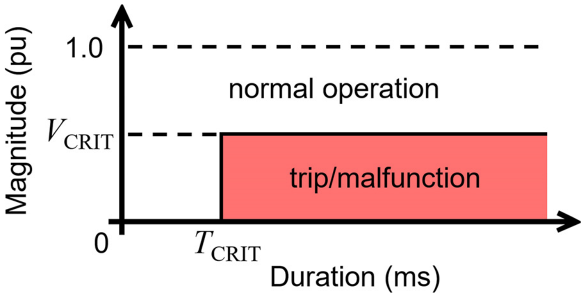


Fig. 1. Rectangular voltage tolerance curve of an equipment.

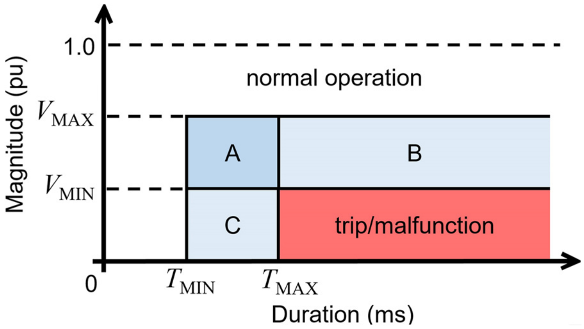


Fig. 2. Uncertainty involved in the behavior of a particular type of equipment against voltage sags.

However, in addition to the fact that different types of loads have different levels of sensitivity, equipment of the same type does not have a single behavior pattern, due to differences in manufacturer, model, etc. Consequently, for each type, there will not be a single sensitivity curve but a family of curves [19]. For example, Fig. 2 illustrates the regions that would be obtained if several samples of a given type of equipment were tested.

Each tested sample would have its own sensitivity curve, defined by a point (T_{CRIT}, V_{CRIT}) inside the region A ($T_{MIN} \le T_{CRIT} \le T_{MAX}$ and $V_{MIN} \le V_{CRIT} \le V_{MAX}$). Voltage sags with magnitude lower than V_{MIN} and duration longer than T_{MAX} would cause the tripping of all samples, whereas none of them would be affected by events with magnitude higher than V_{MAX} or duration shorter than T_{MIN}. In turn, the events in regions A, B, and C would lead to the failure of some samples, but not all of them. Therefore, these regions represent an uncertainty regarding the load response to voltage sags.

Knowing how the variables V_{CRIT} and T_{CRIT} are distributed between V_{MIN} and V_{MAX} and between T_{MIN} and T_{MAX}, respectively, it is possible to estimate the number of trips of the equipment. The distribution of these variables can either be obtained by testing a large number of samples, or by assuming a specific distribution [19]. Considering V_{CRIT} and T_{CRIT} as discrete random variables, we have the following probability mass functions:

$$\begin{aligned} f_{V_{CRIT}}(y) &= P(V_{CRIT} = y) \\ f_{T_{CRIT}}(x) &= P(T_{CRIT} = x) \end{aligned} \tag{2}$$

Thus, the probability of the knee of the equipment's sensitivity curve occurring in point (x, y) is equal to the probability of V_{CRIT} being equal to y and T_{CRIT} being equal to x, which is given by $P_{curve}(x, y)$ from Eq. (3).

$$P_{curve}(x,\ y) = f_{V_{CRIT}}(y).\, f_{T_{CRIT}}(x) \tag{3}$$

In this way, the probability of an event with magnitude *Ve* and duration *Te* resulting in the equipment trip can be calculated from the sum of the probabilities associated to the sensitivity curves that encompass this event, that is, the curves defined by values of V_{CRIT} higher than *Ve* and values of T_{CRIT} lower than *Te*. Thus, considering the following cumulative distribution functions:

$$F_{V_{CRIT}}(y) = P(V_{CRIT} \le y)$$
$$F_{T_{CRIT}}(x) = P(T_{CRIT} \le x) \quad (4)$$

the trip probability of the equipment can be calculated by Eq. (5).

$$P_{trip}(Te,\ Ve) = (1 - F_{V_{CRIT}}(Ve)).\ F_{T_{CRIT}}(Te) \quad (5)$$

where P_{trip} (Te, Ve) is the trip probability due to an event of magnitude Ve and duration Te.

Finally, the number of trips of this type of equipment can be estimated from the sum of the contribution of all events recorded in the site during the month, according to Eq. (6).

$$ENT = \sum_{i=1}^{n} P_{trip}(Te_i,\ Ve_i) \quad (6)$$

where ENT is the estimated number of trips, Ve_i and Te_i are the magnitude and duration of the event i, respectively, and n is the number of events recorded in the reference month.

3.3. Additional considerations for three-phase equipment

Different combinations of three phase voltages during the sag have different effects on the operation of a three-phase equipment [15]. Therefore, to evaluate the performance of these loads, an alternative is to consider different sensitivity levels for each of the three types of sags defined below, as recommended in Ref. [3]:

- type I: the voltage in one phase drops much more than the other two voltages;
- type II: the voltage in two phases drops much more than in the third one;
- type III: the three voltages drop the same amount.

The method proposed in Ref. [20] can be used to classify the events. The first step is to sort the three retained voltages in ascending order, V_X, V_Y, and V_Z, where $V_X \le V_Y \le V_Z$. Then a distinction is made between type I and type II sags considering the following conditions:

- if $(V_Z - V_Y) < (V_Y - V_X)$: the highest retained voltages are close to each other, indicating that it may be a sag of type I or type III;
- if $(V_Z - V_Y) \ge (V_Y - V_X)$: the lowest retained voltages are close to each other, indicating that it may be a sag of type II or type III.

For the distinction between type I and type III, the average of the two highest retained voltages is compared with the lowest voltage [3]:

- if $(V_Y + V_Z)/2 < (0.3 + 0.7\,V_Z)$: the event is type III;
- if $(V_Y + V_Z)/2 \ge (0.3 + 0.7\,V_Z)$: the event is type I.

A distinction is made between type II and type III in a similar way: the highest retained voltage is compared with the average of the two lowest voltages [3]:

- if $V_Z < [0.3 + 0.7\,(V_X + V_Y)/2]$: the event is type III;
- if $V_Z \ge [0.3 + 0.7\,(V_X + V_Y)/2]$: the event is type II.

After performing the classification of all sags recorded in the database, the number of trips of the three-phase equipment is estimated considering type I, type II, and type III events separately. Then, the ENT values are obtained from the sum of the number of trips due to each sag type, month on month.

3.4. Determining a weighting factor for each class of the magnitude-duration table

Considering how the IF index is calculated, it is expected that the more correlated the weighting factors are with the sensitivity level of a given type of equipment, the greater the coefficient r between this index and the number of trips of this equipment will be.

Logically, the ideal would be to define the weighting factors according to the events severity. Observing Fig. 2, a weight equal to 1 could be assigned to events with magnitude lower than V_{MIN} and duration longer than T_{MAX}, and a weight equal to 0 to events with magnitude higher than V_{MAX} or duration shorter than T_{MIN}, whereas the events in regions A, B, and C would receive a weight between 0 and 1. This can be done using Eq. (5).

Thus, based on this equation, a weighting factor is calculated for each class of Table 1, aiming to obtain weights directly proportional to the trip probability of the equipment. However, as these classes are delimited by two values of magnitude and duration, whereas Eq. (5) uses only a single value of Ve and Te, we consider the average between the minimum and the maximum trip probability associated to each class, according to Eq. (7).

$$wf_i = \frac{1}{2}(P_{trip}(Tl_i,\ Vu_i) + P_{trip}(Tu_i,\ Vl_i)) \quad (7)$$

where Vl_i and Tl_i are the lower limits of magnitude and duration of class i, respectively, and Vu_i and Tu_i are the upper limits.

This is done for all types of equipment considered in the analysis, thereby, a set of weights is obtained for each of them. In the case of a three-phase equipment, as distinct levels of sensitivity are defined for each sag type, there will be three set of weights. Thus, Eq. (8) is used so as to obtain a single value of wf by class.

$$wf_i = \frac{1}{n_{total}}(n_{(I)}.\ wf_{(I)i} + n_{(II)}.\ wf_{(II)i} + n_{(III)}.\ wf_{(III)i}) \quad (8)$$

where $wf_{(I)i}$, $wf_{(II)i}$, and $wf_{(III)i}$ are the weights obtained for class i considering the equipment sensitivity to voltage sags of type I, II, and III, respectively; $n_{(I)i}$, $n_{(II)i}$, and $n_{(III)i}$ represent the number of events of each type; and n_{total} is the total number of sags in the database.

Lastly, the weighting factors relative to each type of equipment are averaged, according to Eq. (9), in order to obtain a single set of weights.

$$wf_i = \frac{1}{n_{eqp}} \sum_{j=1}^{n_{eqp}} wf_{ij} \quad (9)$$

where wf_{ij} is the weighting factor obtained for class i relative to equipment j, and n_{eqp} is the number of equipment considered in the analysis.

3.5. Forming regions of sensitivity

As a result of the previous step, a weighting factor is assigned to each class of Table 1. To reduce the number of parameters considered in the calculation of the Impact Factor, it is possible to group the classes with values of wf close to each other, thus forming new regions of sensitivity.

3.6. Determining a weighting factor for each region of sensitivity

As a region of sensitivity is formed by the grouping of more than one class and each class has its own weighting factor, it is necessary to establish criteria to define the weight that will be assigned to each region. The criterion established here is to test several combinations of weights, selecting the one that produces the “best” results based on the Pearson’s correlation coefficient between the IF index and the monthly values of ENT.

Each combination of weights results in a distinct set of Impact Factor values. Therefore, the values of coefficient r must also be updated when a new combination is considered. The number of tests may be higher depending on the number of regions of sensitivity, the range of variation of the weights in each of them and the step sizes. However, as only the weighting factors vary (the number of events by region of sensitivity and the ENT values remain the same), one can easily create a

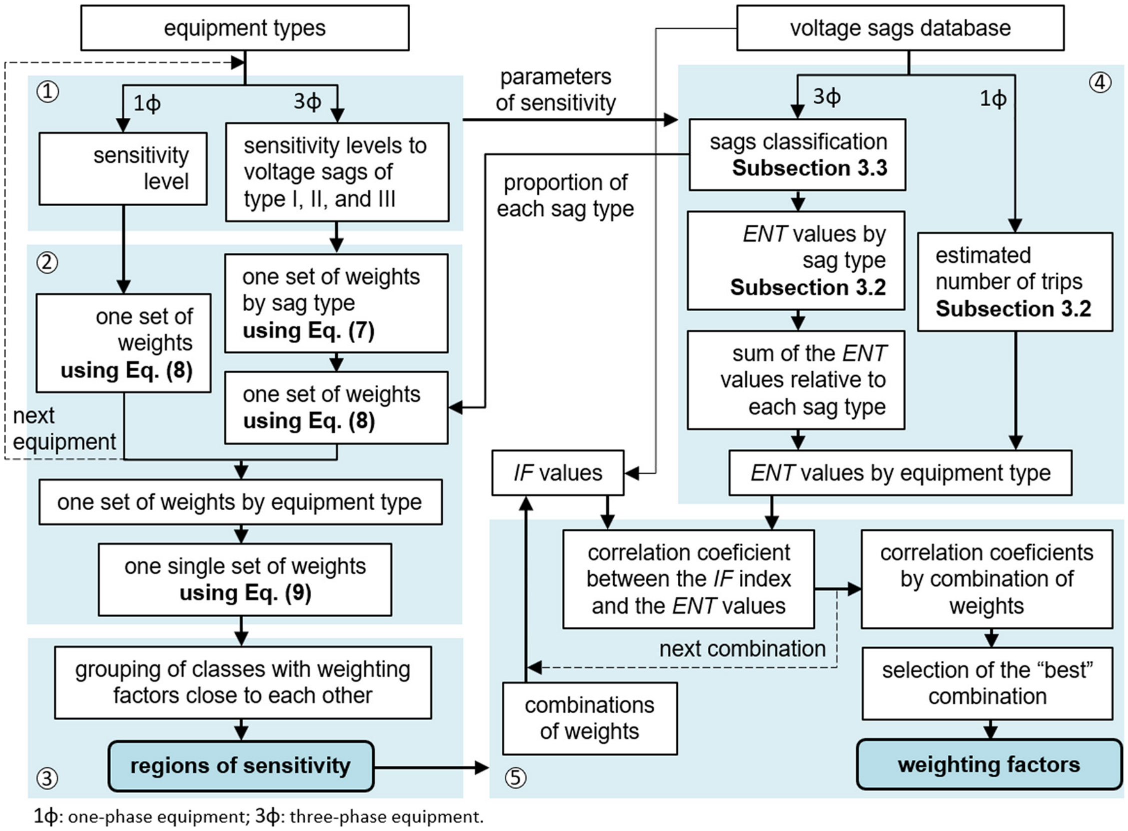


Fig. 3. Procedure flow chart of the proposed methodology.

computational routine that automatically recalculates the *IF* values and the n_{eqp} values of coefficient *r* for all combinations of weights. Then, the combination that best meets some predefined requirements is selected. For example, we could select the combination of weights that results in all values of coefficient *r* greater than a chosen limit, or the combination that results in the highest average value of *r*.

3.7. Procedure flow chart of the methodology

A procedure flow chart of the proposed methodology is presented in Fig. 3.

Blocks 1–5 correspond to:

1. Determination of the parameters of sensitivity relative to each equipment type;
2. Definition of the weighting factors by class of the magnitude-duration table;
3. Formation of the regions of sensitivity;
4. Estimation of the number of equipment trips;
5. Determination of the weighting factors by region of sensitivity.

Some of the indexes in the literature do not take the equipment sensitivity into account, and it is known that this is an important aspect when evaluating the impact of voltage sags on consumers. Other indexes are calculated based on generic sensitivity curves and are easily applicable in obtaining site indexes, however, they do not represent the response of all equipment types and, besides that, these curves do not consider the uncertainty involved in the equipment sensitivity nor the response of three-phase loads to different types of voltage sags. In contrast, the indexes that allow to incorporate these aspects have calculation parameters that are dependent on the equipment type, which makes it difficult to use them to compute site indexes.

By applying the proposed methodology, the calculation parameters of the *IF* index are defined based on the sensitivity level of the chosen equipment. In the case of three-phase loads, it is possible to consider different sensitivity levels against each sag type. The weights by class of the magnitude-duration table are obtained from the combination of the weights adjusted for each equipment. Then, the regions of sensitivity are formed, whose weighting factors are adjusted based on the correlation coefficient between the *IF* index and the *ENT* values. Once the regions of sensitivity and weighting factors are defined, the calculation of the Impact Factor at a site, in a given month, is quite simple.

4. Application of the proposed methodology

This section illustrates the application of the proposed methodology, providing further details about each step by means of a case study.

4.1. Voltage sags database

The variables used in the proposed methodology were calculated from the database of a research and development (R&D) project carried out by two distribution companies from the southeast region of Brazil (EDP São Paulo and EDP Espírito Santo), and by the Federal University of Itajubá. This database is composed by voltage sags monitoring results obtained from 60 PQ monitors, installed at different distribution buses belonging to the two companies (30 monitoring sites in each of them) during a period of one year.

4.2. Equipment types considered in the analysis

Three types of equipment commonly used in most industrial processes have been chosen: programmable logic controllers (PLCs), computers, and adjustable speed drives (ASDs), which show approximately rectangular sensitivity curves [15,21–24].

Table 5
Parameters of sensitivity adopted for each equipment type.

Equipment type	V_{MIN} (%)	V_{MAX} (%)	T_{MIN} (ms)	T_{MAX} (ms)
PLC	25	80	20	400
Computer	25	65	40	450
ASD (type I sags)	15	85	10	450
ASD (type II sags)	45	85	10	175
ASD (type III sags)	55	90	10	150

As already discussed, instead of defining only the parameters V_{CRIT} and T_{CRIT} (see Fig. 1) and considering a single sensitivity curve for each equipment type, we define the parameters V_{MIN}, V_{MAX}, T_{MIN}, and T_{MAX} (see Fig. 2), in order to consider the variation in loads' response to voltage sags. Table 5 shows the values adopted for these parameters, based on published results of equipment testing or on the values adopted in other works: PLC ([12,16,23–26]), computer ([12,16,22,25–27]), and ASD ([12,15,16,21,25,26]).

Three-phase ASDs are considered in this case, which is why we define three levels of sensitivity for this equipment, each of them relative to one of the three types of voltage sags. To estimate the number of trips of a three-phase load, in a given month and at a certain monitoring site, the method presented in Subsection 3.2 is applied considering each sag type separately, then, the three values of *ENT* are added. The method described in Subsection 3.3 is used for classifying the events.

Other types of equipment may also be included in the analysis. If the equipment has nonrectangular sensitivity curves, the first step would be to attempt to make an approximation. For example, some modifications are presented in Ref. [19] aiming to estimate the number of trips of contactors.

With respect to the distribution of the variables V_{CRIT} and T_{CRIT}, since there is nothing to justify the adoption of a specific distribution, it is assumed in this paper that both variables are normally distributed, resulting in a bivariate normal distribution for the points (T_{CRIT}, V_{CRIT}) inside the region A (see Fig. 2).

4.3. Correlation between the Impact Factor and the estimated number of equipment trips

As the adjustment of the calculation parameters of the *IF* index is performed based on its correlation with the estimated number of equipment trips, it is considered relevant to present the results of the correlation analyses carried out in each step, in order to better understand the introduced methodology. In this way, we first present the results considering the *IF* values calculated according to Prodist [6], which are shown in Table 6.

The p-values obtained from the corresponding tests for significance of correlation are also presented. All analyses assume a significance level (α) of 0.05, which is a value commonly used in these tests [28]. If the p-value is less than α, there is strong evidence that the correlation between the variables is statistically significant, which happens in the three cases shown in Table 6. For further details about the statistical concepts, we recommend reading Ref. [28].

The values of coefficient *r*, in turn, indicate that the weights presented in Table 3 appear to be well correlated with the level of sensitivity of ASDs, and to a lesser extent, with the level of sensitivity of PLCs and computers. However, there may be a large variation between the values obtained for different equipment, which makes it difficult to achieve an adjustment that satisfactorily represents all the equipment types under analysis.

Table 6
Pearson's correlation coefficients considering the *IF* values calculated according to Prodist.

Equipment type	PLC	Computer	ASD
Coefficient *r*	0.739	0.624	0.874
p-Value	< 0.001	< 0.001	< 0.001

4.4. Weighting factors by class of the magnitude-duration table

As described in Subsection 3.4, a weighting factor is calculated for each class of Table 1 from Eq. (7), and a set of weights is obtained for each equipment type. Tables 7 and 8 indicate the weights adjusted for PLCs and computers, respectively. In the case of ASDs, as different sensitivity levels are defined for each sag type, it is as if three different types of equipment were treated, thereby, we obtain the sets of weights presented in Tables 9, 10 and 11 .

As can be seen, these sets of weights are the reflection of the values defined in Table 5, that is, they vary according to the parameters of sensitivity adopted for each equipment type.

Equation (8) is applied to define a single set of weights for ASDs. For this purpose, we consider the proportion of events shown in Table 12, which were calculated from the classification of all sags recorded in the database. The results are presented in Table 13.

Tables 7, 8, and 13 indicate the weighting factors that would be obtained if the methodology were applied considering a single equipment type (PLCs, computers, and ASDs, respectively). Table 14 presents the results of the correlation analyses based on these sets of weights.

As expected, the correlation coefficient between the Impact Factor and the number of trips of certain equipment is higher when we consider the *IF* values calculated from the weights adjusted for this same equipment type (note that the diagonal values in Table 14 are higher than the off-diagonal values). So, to establish a single set of weights for these types of equipment, we could consider the weighted average of Tables 7, 8, and 13. However, in this paper we consider the arithmetic average, so as not to prioritize any specific type of equipment. Therefore, the weights presented in Table 15 are obtained from Eq. (9), and the corresponding results of the correlation analyses are shown in Table 16.

When considering the average weights instead of the weights adjusted for a certain equipment type, there is a reduction in the respective correlation coefficient, as can be verified by comparing the values of *r* indicated in Table 16 with the diagonal values of Table 14. However, the difference between the highest and the lowest correlation coefficient decreases, resulting in more balanced values of *r*, which is better in this case, since our objective is to achieve an adjustment that is satisfactory for all equipment types considered in the analysis, and not just for one of them.

4.5. Regions of sensitivity

Once the weighting factors by class are obtained, the classes with values close to each other can be grouped so as to reduce the number of parameters considered in the calculation of the *IF* index. In this paper, we decided to perform the grouping indicated in Table 15, which led to the formation of the regions of sensitivity shown in Table 17.

4.6. Weighting factors by region of sensitivity

As described in Subsection 3.6, to determine a weighting factor for each region of sensitivity, several combinations of weights are tested, in order to select the one that best meets certain predefined requirements. For this purpose, we considered the following ranges of variation and step sizes, based on the values presented in Table 15:

- Region B: from 0.02 to 0.08 in steps of 0.01;
- Region C: from 0.10 to 0.18 in steps of 0.01;
- Region D: from 0.20 to 0.38 in steps of 0.02;
- Region E: from 0.40 to 0.58 in steps of 0.02;

Table 7
Weighting factors for PLCs.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70–80	0.00	0.01	0.01	0.01	0.01	0.01	0.01
60–70	0.00	0.08	0.09	0.09	0.09	0.09	0.09
50–60	0.01	0.30	0.39	0.40	0.40	0.40	0.40
40–50	0.01	0.46	0.77	0.78	0.78	0.78	0.78
30–40	0.01	0.48	0.95	0.97	0.97	0.97	0.97
20–30	0.01	0.49	0.97	1.00	1.00	1.00	1.00
10–20	0.01	0.49	0.98	1.00	1.00	1.00	1.00
≤10	0.01	0.49	0.98	1.00	1.00	1.00	1.00

Table 8
Weighting factors for computers.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70–80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60–70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50–60	0.00	0.08	0.10	0.10	0.10	0.10	0.10
40–50	0.00	0.33	0.48	0.50	0.50	0.50	0.50
30–40	0.00	0.41	0.83	0.90	0.90	0.90	0.90
20–30	0.00	0.42	0.91	1.00	1.00	1.00	1.00
10–20	0.00	0.42	0.91	1.00	1.00	1.00	1.00
≤10	0.00	0.42	0.91	1.00	1.00	1.00	1.00

Table 9
Weighting factors for ASDs considering only type I sags.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70–80	0.00	0.01	0.01	0.01	0.01	0.01	0.01
60–70	0.00	0.07	0.09	0.09	0.09	0.09	0.09
50–60	0.00	0.22	0.32	0.33	0.33	0.33	0.33
40–50	0.01	0.37	0.64	0.67	0.67	0.67	0.67
30–40	0.01	0.43	0.85	0.91	0.91	0.91	0.91
20–30	0.01	0.44	0.92	0.99	0.99	0.99	0.99
10–20	0.01	0.44	0.93	1.00	1.00	1.00	1.00
≤10	0.01	0.44	0.93	1.00	1.00	1.00	1.00

Table 10
Weighting factors for ASDs considering only type II sags.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70–80	0.06	0.10	0.10	0.10	0.10	0.10	0.10
60–70	0.25	0.46	0.50	0.50	0.50	0.50	0.50
50–60	0.31	0.75	0.90	0.90	0.90	0.90	0.90
40–50	0.31	0.81	1.00	1.00	1.00	1.00	1.00
30–40	0.31	0.81	1.00	1.00	1.00	1.00	1.00
20–30	0.31	0.81	1.00	1.00	1.00	1.00	1.00
10–20	0.31	0.81	1.00	1.00	1.00	1.00	1.00
≤10	0.31	0.81	1.00	1.00	1.00	1.00	1.00

Table 11
Weighting factors for ASDs considering only type III sags.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.03	0.04	0.04	0.04	0.04	0.04	0.04
70–80	0.29	0.37	0.38	0.38	0.38	0.38	0.38
60–70	0.42	0.79	0.84	0.84	0.84	0.84	0.84
50–60	0.42	0.92	1.00	1.00	1.00	1.00	1.00
40–50	0.42	0.92	1.00	1.00	1.00	1.00	1.00
30–40	0.42	0.92	1.00	1.00	1.00	1.00	1.00
20–30	0.42	0.92	1.00	1.00	1.00	1.00	1.00
10–20	0.42	0.92	1.00	1.00	1.00	1.00	1.00
≤10	0.42	0.92	1.00	1.00	1.00	1.00	1.00

Table 12
Proportion of voltage sags of type I, II, and III.

$n_{(I)}/n_{total}$	$n_{(II)}/n_{total}$	$n_{(III)}/n_{total}$
0.601	0.265	0.134

- Region F: from 0.86 to 1.00 in steps of 0.02;
- Region G: from 0.60 to 0.84 in steps of 0.02.

Thereby, 655,200 different combinations of weights were tested altogether. The Impact Factor and the values of coefficient *r* were recalculated for each of them. To select the "best" combination, we considered only those in which values of coefficient *r* greater than or equal to 0.900 were obtained for the three types of equipment, and among these combinations, we selected the one with the highest average value of coefficient *r*.

Table 18 shows the selected weighting factors. The results of the correlation analyses relative to this combination are given in Table 19.

With this, the regions of sensitivity and respective weighting factors to be used in the calculation of the Impact Factor would be finally determined. Comparing Tables 6 and 19, it can be observed that, when considering these new parameters, there is a significant increase in the correlation coefficients associated to the three types of equipment.

5. Conclusions

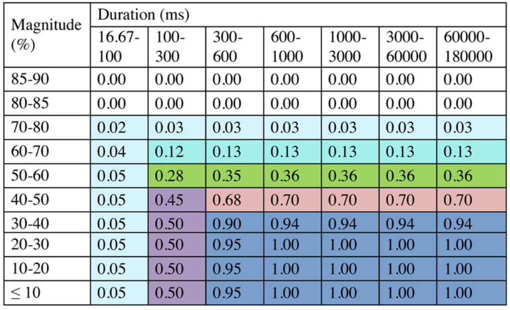
This paper presented a methodology for determining an index that could be applied to evaluate the sites' performance to voltage sags, in view of specific aspects related to the response of sensitive loads. The methodology was developed in order to incorporate to the index calculation the uncertainty involved in equipment sensitivity, as well as the influence of unbalanced sags on three phase loads.

As a result of this methodology, it is possible to define a single set of

Table 14
Pearson's correlation coefficients considering the *IF* values calculated from the weighting factors obtained for each equipment type.

Weighting factors	PLC	Computer	ASD
Table 7	0.967	0.918	0.901
Table 8	0.952	0.966	0.812
Table 13	0.908	0.826	0.931

Table 15
Weighting factors by class of the magnitude-duration table.



Magnitude (%)	Duration (ms)						
	16.67-100	100-300	300-600	600-1000	1000-3000	3000-60000	60000-180000
85-90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80-85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70-80	0.02	0.03	0.03	0.03	0.03	0.03	0.03
60-70	0.04	0.12	0.13	0.13	0.13	0.13	0.13
50-60	0.05	0.28	0.35	0.36	0.36	0.36	0.36
40-50	0.05	0.45	0.68	0.70	0.70	0.70	0.70
30-40	0.05	0.50	0.90	0.94	0.94	0.94	0.94
20-30	0.05	0.50	0.95	1.00	1.00	1.00	1.00
10-20	0.05	0.50	0.95	1.00	1.00	1.00	1.00
≤ 10	0.05	0.50	0.95	1.00	1.00	1.00	1.00

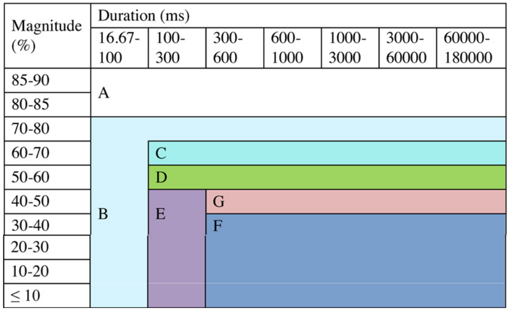
Table 16
Pearson's correlation coefficients considering the *IF* values calculated from the weighting factors given in Table 15.

Equipment type	PLC	Computer	ASD
Coefficient *r*	0.958	0.911	0.908
p-Value	< 0.001	< 0.001	< 0.001

Table 13
Weighting factors for ASDs.

Magnitude (%)	Duration (ms)						
	16.67–100	100–300	300–600	600–1000	1000–3000	3000–60,000	60,000–180,000
85–90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80–85	0.00	0.01	0.01	0.01	0.01	0.01	0.01
70–80	0.05	0.08	0.08	0.08	0.08	0.08	0.08
60–70	0.12	0.27	0.30	0.30	0.30	0.30	0.30
50–60	0.14	0.45	0.56	0.57	0.57	0.57	0.57
40–50	0.14	0.56	0.78	0.80	0.80	0.80	0.80
30–40	0.15	0.60	0.91	0.95	0.95	0.95	0.95
20–30	0.15	0.60	0.95	0.99	0.99	0.99	0.99
10–20	0.15	0.61	0.96	1.00	1.00	1.00	1.00
≤10	0.15	0.61	0.96	1.00	1.00	1.00	1.00

Table 17
Regions of sensitivity formed by grouping the classes.



Magnitude (%)	Duration (ms) 16.67-100	100-300	300-600	600-1000	1000-3000	3000-60000	60000-180000
85-90	A	A	A	A	A	A	A
80-85	A	A	A	A	A	A	A
70-80	B	B	B	B	B	B	B
60-70	B	C	C	C	C	C	C
50-60	B	D	D	D	D	D	D
40-50	B	E	G	G	G	G	G
30-40	B	E	F	F	F	F	F
20-30	B	E	F	F	F	F	F
10-20	B	E	F	F	F	F	F
≤ 10	B	E	F	F	F	F	F

Table 18
Weighting factors by region of sensitivity.

Region of sensitivity	Weighting factor (*wf*)
A	0.00
B	0.04
C	0.16
D	0.30
E	0.46
F	1.00
G	0.82

Table 19
Pearson's correlation coefficients relative to the selected combination of weighting factors.

Equipment type	PLC	Computer	ASD
Coefficient r	0.958	0.913	0.901
p-Value	< 0.001	< 0.001	< 0.001

calculation parameters from which the value of the site's index may be obtained directly. The correlation coefficient between the index and the estimated number of equipment trips is used to compare the adjustments of these parameters, so as to select the adjustment that better represents the sensitivity level of different types of loads.

The Impact Factor, current index in Brazil, is used as basis for applying the proposed methodology. A case study was carried out taking into consideration the real measurement data obtained from 60 monitoring points during a period of one year. Through this study, it was shown how the regions of sensitivity and their respective weighting factors can be defined in order to maximize the correlation between this index and the estimated number of trips of PLCs, computers, and ASDs. It is worth mentioning that other types of equipment can also be included in the analysis.

Therefore, it may be concluded that this work contributed effectively to the improvement and consolidation of voltage sags regulation in Brazil. The obtained results, analyzed in the light of the correlation coefficients, show the acquired gains with the definition of the new regions of sensitivity and weighting factors.

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