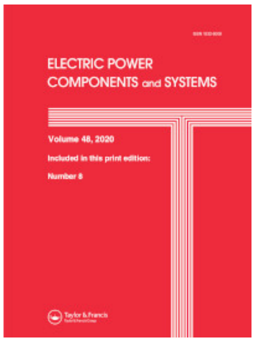

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CONTENTS

Abstract——Since voltage interruptions, sags and swells are Power Quality (PQ) disturbances with great economic impact, studies that seek alternatives to mitigate its effects have been conducted extensively. The PQ Brazilian standard names these disturbances as Short-Duration Voltage Variations (SDVVs), classified them in terms of magnitude, duration, and frequency of occurrence. These parameters are used to calculate the Impact Factor (IF) of SDVVs, a severity-characterization index of their incidence. In this context, this work assesses the influence of three-phase transformer winding connection and neutral grounding on the quantities of SDVVs and the IF observed by an industrial consumer in a distribution system. Fault simulations at ATP-EMTP perform the study, considering two different winding connections for the secondary transformer and applying a grounding resistance to the neutral of the main transformer of the distribution system. The SDVVs are verified in two different ways: phase-to-ground and phase-to-phase voltages. It is observed that there are differences in these quantities and for the value of the IF due to the winding connection of the secondary transformer, the value of the neutral grounding resistance of the main transformer and the ways of voltage verification.

Keywords: neutral grounding, transformer winding connection, voltage sags, voltage swells, interruptions, mitigation, short-duration voltage variation, power quality, load connection, distribution system
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1. INTRODUCTION

Voltage disturbances cause great economic losses for industrial consumers, owing to production stops, raw material losses and manufacturing defects generated by the tripping of sensitive equipment [1]. A general classification for some of the electrical voltage disturbances is the so-called Short-Duration Voltage Variations (SDVVs), which include short voltage interruptions, swells, and sags. These disturbances can be categorized and quantified concerning their severity and frequency of occurrence, yielding the composition of Power Quality (PQ) indicators, such as the Impact Factor (IF) proposed in the Brazilian standard PRODIST, which uses a magnitude-duration stratification

NOMENCLATURE

Dyg	delta–grounded-wye (transformer connection)
EPS	electric power systems
IF	Impact Factor
LG	single-line-to-ground
LL	line-to-line
LLG	two-line-to-ground
LLLG	three-line-to-ground
PQ	Power Quality
PRODIST	Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional
SDVV	Short-Duration Voltage Variations
Y	wye (connection)
YGyg	grounded-wye–grounded-wye (transformer connection)
i	sensitivity region, denoted by A, B, C, D, E, F, G, H and I
f_{en}	frequency of SDVV occurrence in each sensitivity region n , during a period of 30 consecutive days
fp_n	weighting factor for each sensitivity region n
IF_{BASE}	Base Impact Factor
t_R^{51} and t_R^{59}	trip times (s) of characteristics 51 and 59, respectively
I	current (A)
I_R^{51}	minimum pick-up current (A) of the characteristic 51
t_R^{D51} and t_R^{D59}	time-dial multipliers (s) of the characteristics 51 and 59, respectively
A_{51}, B_{51} and p_{51}	constants, which define of the characteristic 51 curve
U and U_n	voltage and nominal voltage (V)
U_R^{59}	minimum pick-up voltage (V) of characteristic 59
A_{59}, B_{59} and p_{59}	constants, which define the characteristic 59 curve
t_F^{MF} and t_F^{MI}	minimum melting and maximum total clear times (s), respectively
i	line where the fault occurs
j	fault or failure type (LG, LL, LLG or LLLG)
k	fault type variation (LG in phase A, B and C, e. g.)
l	fault resistance value
m	phase of node B where the voltage is checked
u_{crit}	critical level voltage
$\Pi_{1\emptyset}$, $\Pi_{2\emptyset}$ and $\Pi_{3\emptyset}$	single-phase, two-phase and three-phase line
N_π	number of lines where the faults are simulated
N_{flt}	number of possible fault types for the line i
N_{ftr}	number of possible failure types for transformers
N_{vfltj}	number of variations for the fault type j
N_{vftrj}	number of variations for the failure type j
N_{rfltj}	number of fault resistances for the fault type j
N_p	number of phases of node B
t_i	fault rate for the line i
t_{fl}	fault rate per km per year in the lines
ℓ_π	total length (m) of line
n_{div}	number of divisions of the line
p_j	probability of the fault type j
p_l	probability of the fault resistance l
u_{Bmijk} and u_{Bmjk}	indication of voltage sag or SDVV occurrence
t and t_f	clearing time for a fuse curve, clearing time of a fuse
t_F^{MF}	minimum melting time (s)
t_F^{MI}	maximum total clear time (s)

[2]. They are mainly originated by faults, transformer energization, and induction-motor starting [3].

The analysis of SDVVs against other PQ events has especial importance for their impact on sensitive equipment, constituting a central concern for manufacturing standards of the technologic industry [4, 5]. While other types of voltage or current disturbances may just lead to an increase in heating and energy loss, like voltage harmonics and unbalance, SDVVs are able to result in process disruptions. Indeed, voltage sags (an SDVV) are the most relevant PQ disturbance for their frequency and the equipment sensibility [4, 6].

In specific cases of faults, computational simulations allow the estimation of SDVVs experienced by sensitive loads, for any level of sensitivity [6, 7], providing a way to assess SDVV mitigation means. Several forms of SDVV mitigation are present on literature, which are related to EPS design, the development of mitigation equipment (designate to interface the sensitive equipment and the system), and, naturally, to the upgrade on the technology of sensitive equipment to handle voltage disturbances with higher tolerances (like the improvement of voltage sag ride-through capability) [6].

Among the mitigation forms related to EPS design are that where is provided some type of redundancy for energy infeed. Examples are the installation of on-site generators near sensitive loads or splitting one substation or bus in two or more ones. Similar to these alternatives it is the system operation with a parallel or loop configuration [6]. On the other side, the use of mitigation equipment is achievable and attractive for costumers. The employed of uninterruptible power supplies (UPSs), voltage source converters (VSCs), motor-generator sets, ferroresonant transformers (or constant voltage transformers [CVT's]) and electronic tap changers are examples [6, 8–11].

Two other possible SDVV-mitigation means can be given through the correct chose of the transformer winding connection that feeds sensitive loads or the neutral grounding practice of the system, since these features determine the voltage relations and the ground-fault levels (which is related to fault-clearing times). As know, for unbalanced faults, the winding connection of transformers located between the fault point and the observation point can significantly alter the characteristics of SDVVs [4, 6, 7].

Classification	Type	Typical duration	Typical voltage magnitude
Momentary	Interruptions	≤3 s	<0.1 pu
	Voltage sags	1 cycle–3 s	0.1–0.9 pu
	Voltage swells	1 cycle–3 s	>1.1 pu
Temporary	Interruptions	>3 s–3 min	<0.1 pu
	Voltage sags	> 3 s–3 min	0.1–0.9 pu
	Voltage swells	>3 s–3 min	>1.1 pu

TABLE 1. SDVV classification according to PRODIST. Based on the information provided by *Agência Nacional de Energia Elétrica*, 2018.

There are changes in phasor voltages passing through transformers when different connections are used for their primary and secondary windings. Furthermore, the load connection can likewise determine how certain loads experience unbalanced SDVVs [6, 12, 13]. Beyond that, the winding connection and the presence or absence of a neutral to ground connection influence the zero-sequence circuit continuity between both sides of a transformer and on the system zero-sequence impedance, which also changes the SDVV characteristics [6, 14–16].

The influence of the transformer winding connections on SDVVs (mostly voltage sags) were commented and evaluated in many works [4, 6, 7, 17–20]. These concepts were introduced in [4] and the possibility of reducing voltage sag problems using transformer winding connections was indicated in [7]. Posterior works [6, 17–19] showed that voltage sags can be sorted into up seven types, which are a function of the fault type and transformer winding and load connections. Moreover, the influence of neutral grounding practice and the value of the zero-sequence impedance on voltages sags were given in [6] and further extended in [13], where their effects during unbalanced ground faults were analytically demonstrated.

Based on the previous works, the present one aims to present an analysis of the changes in the voltage sag levels and the IF index observed by an industrial consumer given modifications in the winding connection of the transformer at its entrance (secondary transformer) and of neutral-grounding resistance of the substation (main) transformer. The results are obtained by fault simulations in an IEEE distribution test feeder, with unbalanced lines and loads, like real ones, using the prediction methodology. The study relates the influence caused on magnitude and duration of the SDVVs, modeling the protection system, thus allowing the SDVV stratification and quantification of the IF index. A massive amount of simulations was performed, considering all faults types with different impedances at all system lines and transformers, with a probabilistic distribution. It is shown that the main transformer grounding impedance and the secondary transformer winding connection clearly influence the voltage sag levels (which are specially analyzed) and the IF value.

This paper is organized as follows. In Section 2, general characteristics of SDVVs, their stratification and the IF calculation according to Brazilian standard PRODIST are introduced. In Section 3, the proposed methodology for SDVV assessment is presented. In Section 4, the results obtained for the case studies are shown and discussed. Finally, in Section 5 the conclusions of the study can be found.

2. CONCEPTS RELATED TO SDVVS: DEFINITION AND STRATIFICATION

2.1. Brazilian Standards for SDVVs

The SDVVs are characterized by a variation in the rms value of the voltage magnitude from the nominal in an interval of time considered short, consisting of voltage interruptions, sags, and swells. The amplitude and duration values contemplated, as well as the ones that defined the classification of each type of SDVV, vary according to the norm applied. On Brazilian standard PRODIST [2], SDVVs are classified according to Table 1, which is a different categorization from that one presented on IEEE standard [21].

2.2. Brazilian Standard PRODIST for SDVV Stratification and IF Calculation

Brazilian standard PRODIST [2] proposes a stratification of SDVVs based on sensitivity levels of different loads, relating the magnitude and the duration, besides their classification. The stratification is performed in nine sensitivity regions, designated by the letters A to G. There are twelve amplitude ranges, encompassing interruptions, sags and swells, and seven duration ones.

Based on this stratification it is possible to determine the IF [2] for the severity characterization of SDVVs. The IF depends on the frequency of events in each sensitivity region for a monitoring period of thirty consecutive days. The higher the frequency and the severity of SDVVs experienced by a sensitive load, the higher the IF; or, to put it another way, the higher the IF for a given observation point of an EPS, the higher the possibility of a sensitive

Amplitude (pu)	Duration						
	[16.67 ms–100 ms]	(100 ms–300 ms]	(300 ms–600 ms]	(600 ms–1 sec]	(1 sec–3 sec]	(3 sec–1 min]	(1 min–3 min)
> 1.15	Region H	Region H	Region H	Region I	Region I	Region I	Region I
(1.10–1.15]	Region H	Region H	Region H	Region I	Region I	Region I	Region I
(0.85–0.90]	Region A	Region A	Region A	Region A	Region A	Region A	Region A
(0.80–0.85]	Region A	Region A	Region A	Region G	Region G	Region G	Region G
(0.70–0.80]	Region B	Region D	Region D	Region G	Region G	Region G	Region G
(0.60–0.70]	Region B	Region D	Region D	Region F	Region F	Region F	Region F
(0.50–0.60]	Region C	Region D	Region D	Region F	Region F	Region F	Region F
(0.40–0.50]	Region C	Region D	Region D	Region F	Region F	Region F	Region F
(0.30–0.40]	Region E	Region E	Region E	Region F	Region F	Region F	Region F
(0,20–0,30]	Region E	Region E	Region E	Region F	Region F	Region F	Region F
(0.10–0.20]	Region E	Region E	Region E	Region F	Region F	Region F	Region F
<0.10	Region E	Region E	Region E	Region F	Region F	Region F	Region F

TABLE 2. Stratification of SDVVs based on sensitivity levels of various loads. Based on the information provided by Agência Nacional de Energia Elétrica, 2018.

load connected in this point to experience an abnormal operation due to SDVVs.

Brazilian Standard attributes weighting factors for each sensitivity region to represent the relevance of the event and defines their values. As higher the weighting factor, more sever the SDVV events on the respective sensitivity region. A Base Impact Factor is obtained from the sum of the products of the weighting factors by the maximum frequencies of SDVV occurrence in each sensitivity region for thirty days. Brazilian standard provides the Base Impact Factor for two ranges of nominal voltages. The weighting factors and the Base Impact Factor are used for the IF calculation. Table 2 presents the nine sensitivity regions and Table 3 the weighting factors along with the Base Impact Factor according to the nominal voltage.

The calculation of the IF is given by Eq. (1),

$$IF = \frac{\sum_{n=A}^{I} (f_{en} \times fp_n)}{IF_{BASE}} \tag{1}$$

PRODIST [2] does not set an IF_{BASE} value for voltage levels below 1 kV (low voltage).

Region	Weighting factor	Base impact factor (IF_{BASE})	
		1.0 kV < V_n < 69 kV	69 kV < V_n < 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 3. Weighting factors for each sensitivity region. Based on the information provided by *Agência Nacional de Energia Elétrica*, 2018.

The PRODIST stratification is unique of this standard and there is no suchlike on IEEE standard [21], representing the impact of SDVVs through a severity-characterization index.

3. METHODOLOGY APPLIED TO THE STUDY

3.1. System Modeling and Simulation

The quantification of the voltage sags number (including short interruptions) and the SDVV stratification for the desired node are obtained through fault simulations. The system is modeled in ATP-EMTP. As SDVVs will present certain characteristics according to the type of fault, its impedance, and its location, these features are changed. Using MATLAB to automatically call a series of simulations, LG, LL, LLG, and LLLG faults are simulated at all system lines and transformers (at their secondary side nodes).

The desired node represents an industrial consumer with sensitive loads. Unbalanced lines are modeled, and therefore different voltage variations caused by unbalanced faults involving different phases are obtained. The system model also contemplates branches with only one or two phases.

3.2. SDVV Magnitude Assessment

The SDVV magnitudes are obtained directly from the measured voltages of ATP-EMTP simulations, which return the instantaneous phase-to-ground voltages. The SDVVs are checked separately for each phase at the industrial consumer node, for phase-to-ground and phase-to-phase voltages: in phases A, B and C for phase-to-ground voltages and in “phases” AB, BC, and AC for the phase-to-phase voltages. It is considered, for the assessment, that loads with a phase-to-neutral connection observe a phase-to-ground SDVV, while loads with a phase-to-phase connection observe a phase-to-phase SDVV.

The rms voltages are calculated from the beginning of the fault until the fault clearing by the protection system. The calculation is always performed at a time interval equivalent to a cycle of instantaneous voltage, being updated each half cycle.

3.3. SDVV Duration Assessment

The operation mechanism of the protection system is also related to SDVVs: an SDVV begins with the fault occurrence and ends with its clearing by the protection system. Thus, the SDVV duration is obtained in this work by the fault clearing time, being the protection system composed by a three-phase recloser at the substation and type K-link expulsion fuses distributed throughout some lateral taps. The protection system is configured in a fuse blowing scheme for overcurrent protection.

The three-phase recloser operates in the inverse-time overcurrent 51, inverse-time overvoltage 59, and auto-reclosing 79 functions. The inverse-time characteristics 51 and 59 are both approximated by Eqs. (2) and (3), respectively, according to [22–25],

$$t_R^{51}(I) = \left(\frac{A_{51}}{\left(I/I_R^{51}\right)^{p_{51}} - 1} + B_{51} \right) \cdot t_R^{D51} \tag{2}$$

$$t_R^{59}(U) = \left(\frac{A_{59}}{\left(U/U_R^{59}\right)^{p_{59}} - 1} + B_{59} \right) \cdot t_R^{D59} \tag{3}$$

The fuse sizes are chosen according to load and fault currents. These are given by the load current of the line terminal node plus the load currents of the downstream nodes and by the current during an LG fault with a 40-Ω resistance [25]. The fuse clearing time is determined by the average between the clearing times respective to the minimum melt and maximum total clear curves, obtained by approximations of both. These results from the nominal time-current curve adjustment by *n-order* polynomial functions [22], using the MATLAB polyfit function [26]. Thus, the clearing time t for a curve (minimum melting or maximum total clear one) is given by Eq. (4)

$$t(I) = 10^{\left[a_n \cdot (\log_{10} I)^n + \cdots + a_1 \cdot \log_{10} I + a_0\right]} \tag{4}$$

and the clearing time t_f of a fuse is given by Eq. (5)

$$t_f(I) = \frac{t_F^{MF}(I) + t_F^{MI}(I)}{2} \tag{5}$$

The rms current used in (2) and (4) is given by the current flow in the protected circuit, obtained in the ATP-EMTP simulations. The recloser verifies the current in a time interval equivalent to a cycle, being updated every quarter cycle. The same procedure is done for the rms voltage used in (3).

3.4. Voltage Sags Quantification According to Critical Levels

For a given node B after a secondary transformer, the events per phase N_{sags_B} is given by (6). In (6), the first term corresponds to line faults and the second ones correspond to the faults in the secondary and main transformers (the $t_{ftr_{ent}}$ and $t_{ftr_{sub}}$ coefficients refer to the failure rates in both transformers, respectively).

$$N_{sags_B} = \sum_{i=1}^{N_\pi} \sum_{j=1}^{N_{flt}} \sum_{k=1}^{N_{vfltj}} \sum_{l=1}^{N_{rfltj}} \sum_{m=1}^{N_p} t_i \cdot \frac{p_j}{N_{vfltj}} . p_l . u_{Bmijk} + \sum_{j=1}^{N_{ftr}} \sum_{k=1}^{N_{vftrj}} \sum_{m=1}^{N_p} (t_{ftr_{ent}} + t_{ftr_{sub}}) \cdot \frac{p_j}{N_{vftrj}} . u_{Bmjk} \tag{6}$$

N_{flt} is equal to 4 for lines $\Pi_{3\emptyset}$, 3 for lines $\Pi_{2\emptyset}$ and 1 for lines $\Pi_{1\emptyset}$. N_{ftr} is equal to 4, 3 and 1 for a three-phase, two-phase and single-phase transformer, respectively. N_{vfltj} is equal to 3 for LG, LL and LLG faults and 1 for LLLG faults in the lines $\Pi_{3\emptyset}$; 2 for LG faults and 1 for LL and LLG faults in the lines $\Pi_{2\emptyset}$; and, 1 for LG faults in the lines $\Pi_{1\emptyset}$. N_{vftrj} is equal to 3 for LG, LL and LLG faults and 1 for LLLG faults for a three-phase transformer; 2 for LG faults and 1 for LL and LLG faults for a two-phase transformer; and, 1 for LG faults for a single-phase transformer. t_i for a given line i is yielded by (7)

$$t_i = t_{fl} \frac{\ell_\pi}{n_{div} - 1} \tag{7}$$

being the fault simulation points formed by n_{div}.

u_{Bmijk} subscripts indicate that the voltage sag or the SDVV occurs in phase m of node B due to the fault type j of variation k in the line i; similarly, u_{Bmjk} subscripts indicate that the disturbance occurs in phase m of node B due to the failure type j of variation k in any transformer. For voltage sags it is considered that u_{Bmijk} is 1 if the voltage in phase m of node B is lower than u_{crit} and 0 if not; for SDVV, u_{Bmijk} indicates its occurrence within limits of some region of Table 3, knowing also the SDVV duration.

3.5. Transformers Winding Connection and Neutral Grounding Assessment

The secondary transformer winding connection is changed by keeping the line voltage and the dispersion impedance percentage values equal for both cases. Also, the value of the neutral grounding impedance of the main transformer is

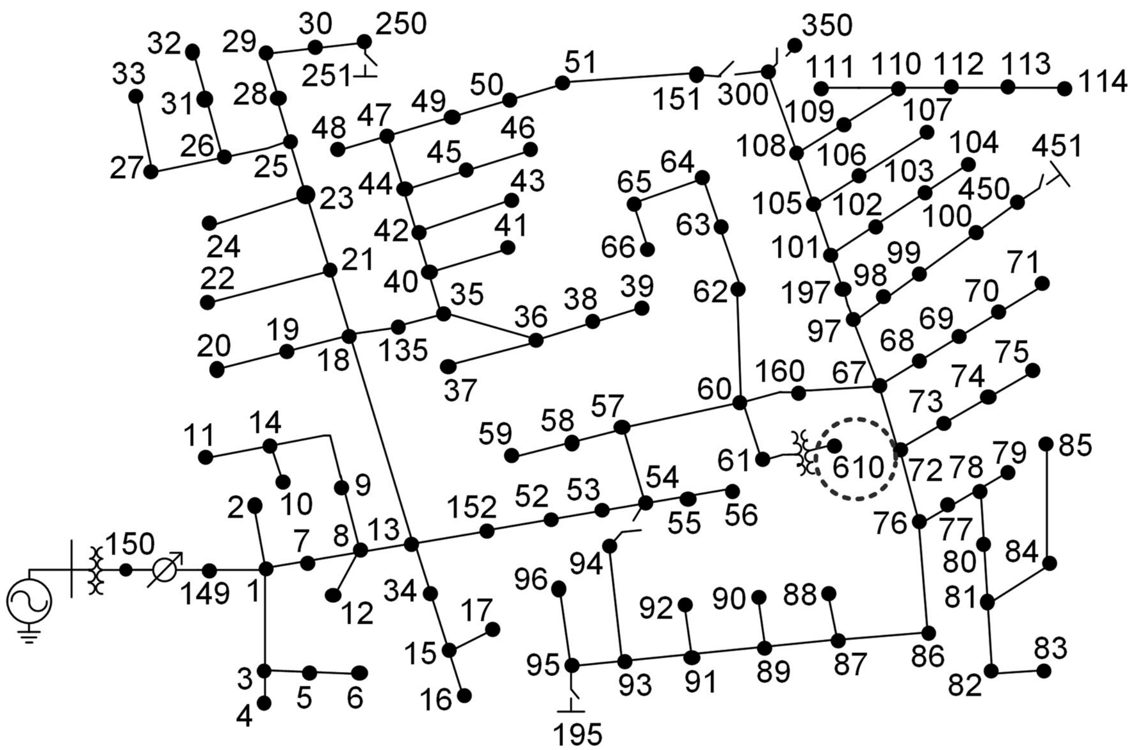

FIGURE 1. IEEE 123 Node Test Feeder. Based on the information provided by Institute of Electrical and Electronics Engineers, 2019.

changed. The neutral grounding impedance used is purely resistive, its values being defined arbitrarily.

The EPS neutral grounding causes a difference between the total positive- and zero-sequence impedances, being directly related to the transformer neutral grounding. Transformer neutral grounding, or, in general, EPS neutral grounding, causes a great influence on temporary overvoltages in non-faulty phases and determines the fault current magnitude during ground faults [14–16]. Therefore, it is a feature that impacts SDVVs.

3.6. Impact Factor Assessment

The SDVV impact is evaluated by calculation of the IF at the observation node for each case study, by assessing the SDVV magnitude and duration. As recommended [2], the temporal aggregation of SDVV events is performed. Consecutive events within three minutes, at the same point, are aggregated composing a single event. The most severe event represents the entire duration. The phase aggregation of the events is also carried out, that is, simultaneous events at several phases are aggregated into a single event [2]. Thus, voltage sags in two or three phases are considered as a single SDVV event. However, a voltage sag and a voltage swell at the same point are treated separately.

4. CASE STUDY

4.1. Simulated Distribution System

The IEEE 123 node test feeder [27] has lines and loads with unbalanced characteristics, also having capacitor banks, voltage regulators and switches. Some of its characteristics are:

- two transformers, the main HV/MV transformer, and one MV/LV secondary transformer;
- 118 lines: 55 three-phase, 3 bi-phase and 55 single-phase unbalanced overhead lines, respectively, and 5 unbalanced underground ones;
- 85 loads: 3 unbalanced and 2 balanced three-phase types and 80 single-phase type; among them, 2 three-phase unbalanced loads are delta-connected and 1 single-phase is wye-connected.

The system was modeled on ATPdraw with adaptations. Figure 1 shows the single line diagram, with the observation point indicated by a circle.

4.2. Substation

The main transformer is connected to a generator with a fault level of 5,000 MVA at the rated voltage of 115 kV. It is modeled by three wye-connected ideal single-phase voltage sources with zero-impedance neutral grounding. The main transformer has a delta/star-grounded winding connection (Dyg). The nominal voltage of the primary side is 115 kV, while the secondary one is 4.16 kV. The values used for the main transformer neutral grounding resistance are 1, 10, 20, 30, 40 and 50 Ω.

4.3. Lines and Loads

The system has twelve line configurations, with differences in the type of conductor, the spacing between each conductor and the presence or not of a neutral conductor. Since all the respective configurations are unbalanced, there are self and mutual impedances and susceptances. The loads are modeled as constant impedance.

4.3. Observation Point

Node 610 represents the industrial consumer with a sensitive load, which is connected to the system by a step-down transformer (the same secondary transformer considered). The nominal voltage at this point is 480 V, being used as a reference voltage to determine the SDVV magnitudes in pu. The system main feeder provides a direct path from the substation to the industrial consumer node.

The connections used for the secondary transformer are YGyg and Dyg, constituting two simulation cases, summarized as:

- secondary transformer YGyg-connected and solidly grounded;
- secondary transformer Dyg-connected and solidly grounded.

The load is three-phase unbalanced resistive-inductive wye-connected, with 160 kW and 110 kvar in the phase A and 120 kW and 90 kvar in both phases B and C.

4.4. Faults

The values of the statistical parameters t_{fl} and p_j of (6) of the assessment were based on EPS fault reported data. From [25], the fault rate used is 2.18 faults (of any type) per km of line per year. The fault rates used for the main and consumer secondary transformers are 0.0614 and 0.59 faults per year, respectively. The probabilities of each fault type in distribution systems were adapted from the values found in [28]: 79% for LG, 12% for LL, 5% for LLG and 4% for LLLG faults. Transformer failures are also considered to fall into the line fault type division (*i.e.* there are LG, LL, LLG, and LLLG faults), though transformer failures may be of other types [29, 30].

Node A	Node B	Fuse	Node A	Node B	Fuse
1	2	10	47	49	15
1	3	10	49	50	10
8	9	10	35	36	10
8	12	10	54	55	10
13	34	10	57	58	10
13	18	100	60	62	25
18	19	10	160	67	65
18	21	10	67	97	10
42	44	65	81	84	10
47	48	25	84	85	6

TABLE 4. Lines with fuses and respective fuse ratings.

The values presented in [25, 31, 32] were chosen for fault resistances, as well as a negligible value to represent bolted faults. The values 0.0001, 5, 20 and 40 Ω are used for the resistance between phase and ground for the LG fault, the values 0.0001 and 5 Ω for the resistance between phases for the LL, LLG, and LLLG faults and the values 0.0001, 5 and 20 Ω for the resistance between phases and ground for the LLG and LLLG faults. The fault resistances of different phases have the same value at LLLG and LLG faults.

4.5. Used Protection System

The values 30, 0.1 and 3.0 are adopted for A_{51}, B_{51} and p_{51} and 30, 0.0 and 5.0 for A_{59}, B_{59} and p_{59}[23]. t_R^{D51} and t_R^{D59} equal to 1 sec and 25 sec are adopted for the reclosing interval, allowing three reclosers, for both characteristics. The value of 260 A is selected for I_R^{51}, and the value of 3,328 kV for V_R^{59}. It is considered that the recloser characteristic 59 will operate by phase-to-ground voltages. The 59-characteristic reach covers the entire system. The characteristic 51 operates only for the main feeder, performing in it the overcurrent protection, owing to the fuse blowing scheme.

Expulsion fuses are placed at the beginning of the lateral taps. Type K-link preferred fuses (6, 10, 15, 25, 40, 65, 100, 140 and 200 A) are chosen, the fuse sizes and their respective lines being shown in Table 4. There are at most two levels of fusing.

5. RESULTS AND DISCUSSION

The waveforms of phase-to-ground voltages at the entrance of the industrial consumer for LG, LL, LLG, and LLLG faults simulated at the node 300 are shown in Figures 2

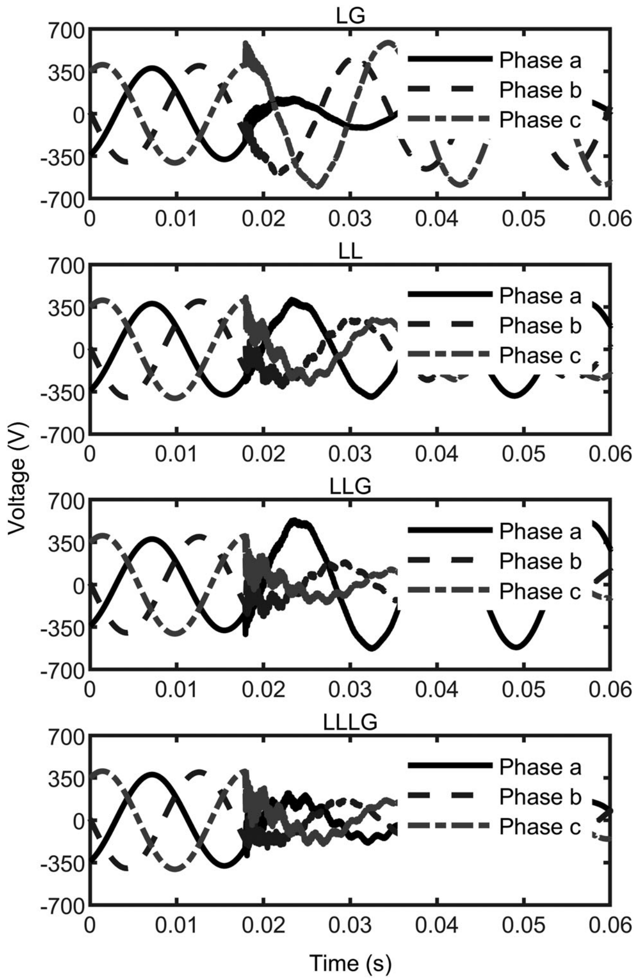

FIGURE 2. Phase-to-ground voltages for case 1 (secondary transformer YGyg-connected).

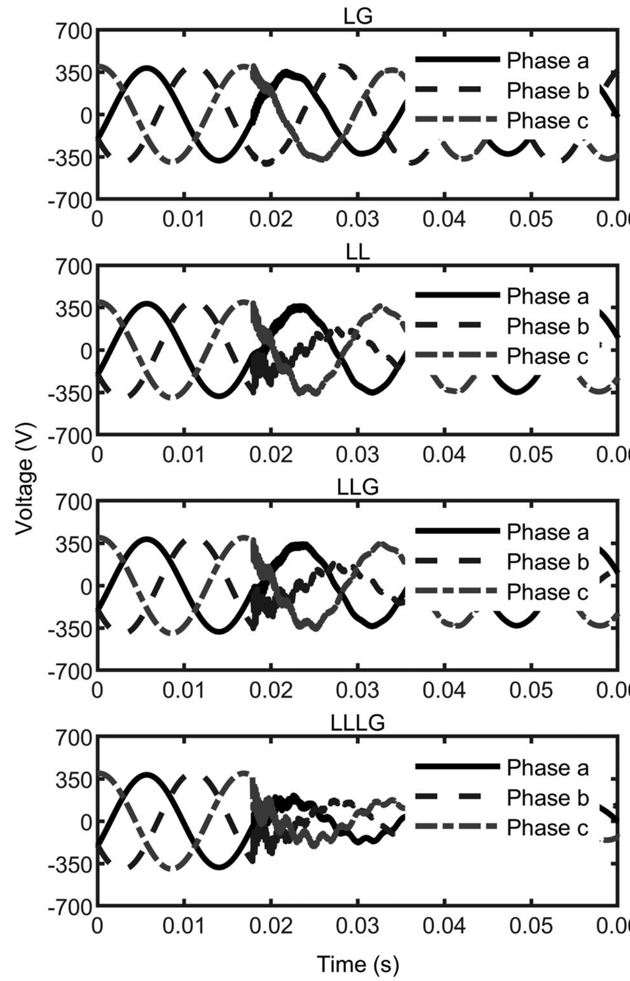

FIGURE 3. Phase-to-ground voltages for case 2 (secondary transformer Dyg-connected).

and 3, when the winding connections of the secondary transformer are YGyg and Dyg, respectively. It was considered a neutral grounding resistance of 1 Ω in the main transformer and the value of 0.0001 Ω for any fault resistances.

The assessment results are shown in Figures 4 and 5 for the cumulative average number of voltage sags observed at the consumer node for each voltage critical level considered in cases 1 and 2, respectively, and for each value of neutral grounding resistance (given at the graphic legend). The IF values for both secondary transformer connections are shown in Table 5. The results are presented for phase-to-ground and phase-to-phase voltages. The voltage critical level, as said before, is the voltage level for which all voltage sags with a lower magnitude are counted, being u_{Bmijk} and u_{Bmjk} of (6).

To normalize the IF obtained and to facilitate the comparison between the cases, the FI_{BASE} used for the phase-to-ground voltages was obtained with the secondary transformer Dyg-connected and the 30-Ω neutral grounding resistance of the main transformer. The FI_{BASE} used for the phase-to-phase voltages was obtained with the YGyg-connection and the 30-Ω neutral grounding resistance of the main transformer.

From Figures 4 and 5 and Table 5, the number of voltage sags for each voltage critical level and the value of IF observed for the industrial consumer of the node 610 vary considerably depending on the secondary transformer and the load connections.

The results show that the neutral grounding resistance of the main transformer for both winding connections of the secondary transformer causes changes above 10% in the average number of voltage sags of any phase-to-ground magnitude. The same changes are about 10% for phase-to-phase voltages. Figures 4 and 5 show that changes in the value of the neutral grounding resistance cause up to 20%

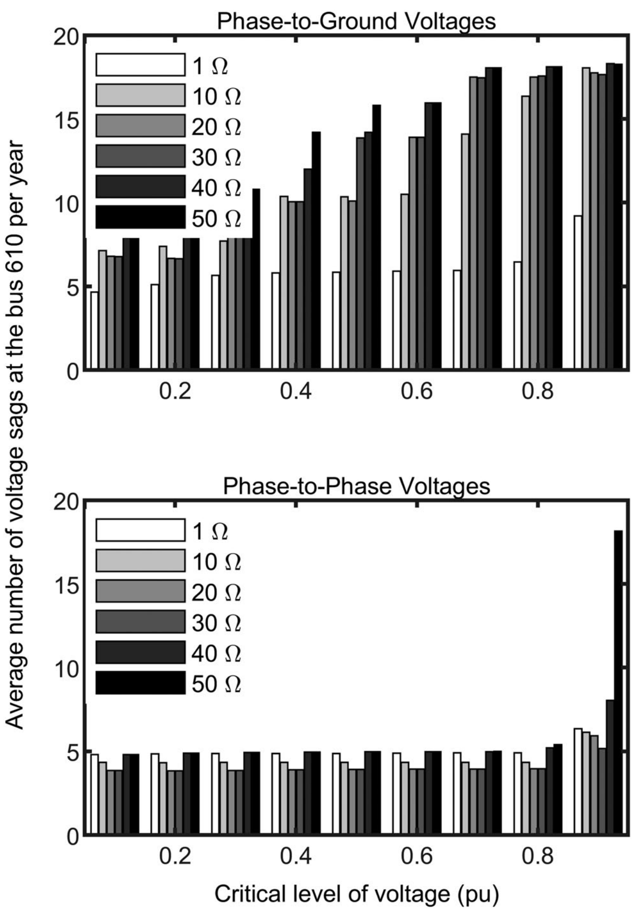

FIGURE 4. Number of voltage sags for case 1 (secondary transformer YGyg-connected).

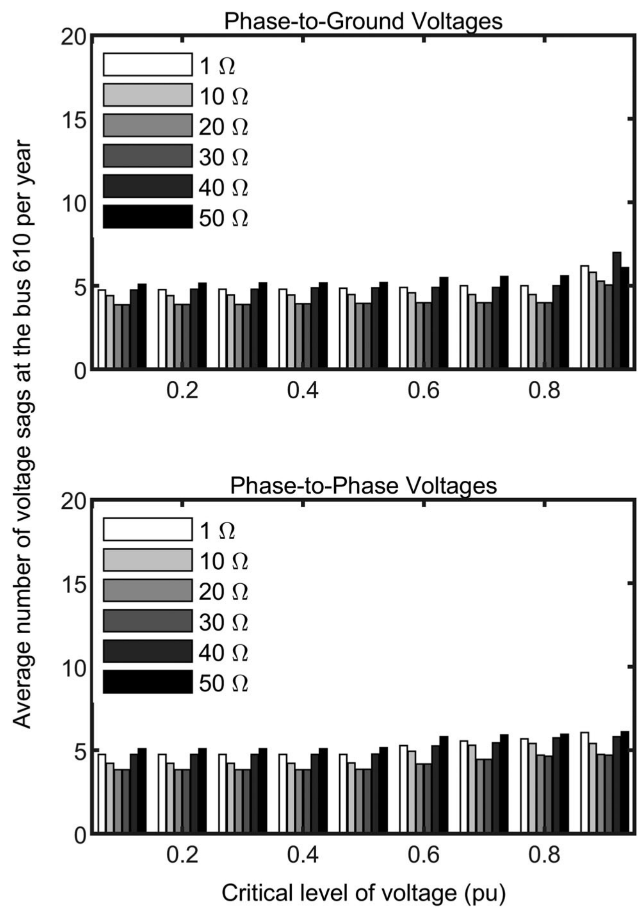

FIGURE 5. Number of voltage sags for case 2 (secondary transformer Dyg-connected).

and 30% fewer phase-to-ground sags with magnitude lower than 0.7 pu when the secondary transformer is YGyg- and Dyg-connected, respectively. There are also 30% fewer phase-to-phase sags lower than 0.7 pu depending on the value of the neutral grounding resistance.

The neutral grounding resistance of the main transformer causes, in general, changes above 10% of the IF value, for both connections of the secondary transformer and for both connections of the load, according to Table 5. There is an increase of the IF value is given an increase of the neutral grounding resistance value for the YGyg-connected secondary transformer and a phase-to-neutral-connected load. For the secondary transformer with a Dyg-connection or a load with a phase-to-phase-connection, the change of the IF value related to the main transformer neutral grounding impedance is more random.

Comparing the two load connections, it can be seen that with the YGyg-connected secondary transformer, for a phase-to-phase-connected load against a phase-to-neutral-connected load, voltage sags with a magnitude below 0.7 pu occur up to four times fewer as shown in Figure 4.

On the other hand, for the Dyg-connected secondary transformer, the reduction of the number of voltage sags with magnitude lower than 0.7 pu is fewer than 10% for a load with a phase-to-neutral-connection respecting a load with a phase-to-phase-connection, as shown in Figure 5.

Grounding resistance (Ω)	Phase-to-ground voltages		Phase-to-phase voltages	
	YGyg	Dyg	YGyg	Dyg
1	1.58	1.14	1.41	1.80
10	5.14	1.09	1.05	1.49
20	6.65	1.02	1.00	1.47
30	7.25	1.00	1.00	1.43
40	7.25	1.16	1.01	1.45
50	7.88	1.24	1.12	1.48

TABLE 5. IF value for cases 1 and 2.

The IF is always higher for a phase-to-neutral-connected load concerning a phase-to-phase-connected load for both YGyg and Dyg connections of the secondary transformer. The differences between the values depend on the value of the neutral grounding resistance of the main transformer.

Comparing the two winding connections of the secondary transformer, it can be observed that, for the YGyg one, there are four times more phase-to-ground voltage sags with magnitude lower than 0.7 pu regarding the Dyg one (Figures 4 and 5).

The IF value is up to six times higher for the YGyg-connected secondary transformer relating to the Dyg-connected one, for a phase-to-neutral-connected load. For a phase-to-phase-connected load, the IF is around 20% to 30% higher for the Dyg-connected secondary transformer respecting the YGyg one (Table 5).

Accordingly, for both types of secondary transformer connections, a significant change in the amount of SDVVs is observed because of the value of the neutral grounding resistance of the main transformer. SDVVs experienced by both phase-to-neutral and phase-to-phase connected loads were affected.

The IF value for a phase-to-phase-connected load is smaller for the secondary transformer with the connection YGyg, for all values of the neutral grounding resistance of the main transformer. Meanwhile, for a load with the phase-to-neutral-connection, the IF is always higher for the YGyg-connected secondary transformer.

It can be concluded from these cases that, for the protection scheme and the values of the neutral grounding resistance used, the best configuration for the secondary transformer connection is the Dyg for a load with a phase-to-neutral-connection. On the other hand, the best connection of the secondary transformer is the YGyg one for a load with a phase-to-phase-connection.

Analyzing the effect of the main transformer neutral grounding resistance, it is concluded that, for both load connections, the values of 20 Ω and 30 Ω presented the lowest number of voltage sags and IF value at the consumer node.

6. CONCLUSION

This paper offers an analysis of the influences of the type of secondary transformer connection and main transformer neutral grounding on SDVVs. The SDVVs were assessed according to the Brazilian standard, with emphasis on voltage sags.

In general, the results show that the SDVVs observed by an industrial consumer, according to the PRODIST stratification, vary considerably depending on the types of the secondary transformer and the load connections.

More significantly, the results indicate that the Dyg is the type of secondary transformer connection that provides less vulnerability to the consumer to SDVVs for phase-to-neutral-connected loads. For phase-to-phase-connected loads, the YGyg-connection is indicated for the secondary transformer. Thus, the secondary transformer Dyg-connection is recommended for consumers with single-phase loads, which are usually connected between one phase and neutral. Nonetheless, the secondary transformer YGyg-connection is recommended for three-phase delta-connected loads (a usual connection for electric motors).

When the neutral grounding of the main transformer was verified, it has been observed that it exerts significant influence on SDVVs experienced by loads, regardless of the types of their connections and the winding connections of the transformers employed for them. The best results were obtained for resistance values in the range of 20 to 30 Ω.

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