Low-Voltage AC Surge Protective Device Assessment regarding Nuclear Plants

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Abstract **- This paper presents a methodology for low-voltage AC surge protective device (SPD) coordination. As motivation, the required nuclear plant reliability and safety criteria, in which the surge protection coordination can assume an important role, are emphasized. Due to the characteristics of the protection system, and the surge phenomena, an iterative methodology is applied. The SPD selection and specifications are based on the equipment immunity level, insulation and on SPD characteristics, like absorbed energy. Some results are presented and discussed, showing the suitability of the proposed methodology.**

Index Terms **–Surge protection coordination, electromagnetic compatibility, risk management, safety requirements.**

I. Introduction

THE low immunity level of electrical and electronic systems, when compared to the present electromagnetic environments, should be emphasized. The high-intensity electromagnetic phenomena like the ones resulting from lightning and switching of electric loads are among the most import phenomena to be considered. Thus, to satisfy the functional safety system requirement, the electromagnetic compatibility (EMC) studies are strongly recommended and assume great importance [1][2].

It mentions the aforementioned aspects concerning nuclear plants: Event analysis resulting from lightning in nuclear power plants are discussed in the literature, like in the License Event Reports (LER) that precedes the preparation of NUREG/CR-6866 [3]. Many events related to undue operations and damages to equipment in nuclear plants are reported. To illustrate it, it mentions that 240 events caused by lightning were recorded, considering the 1980-2003 event analysis period [3].

Regarding the SPD coordination, it is also stressed that the installation of SPD only in one-stage, near sensitive equipment, is not suitable for achieving the system protection. Thus, it is necessary to apply SPD in more than one-stage (cascade), from the panel board distribution to the sensitive equipment [4].

This paper presents an iterative methodology to optimize the SPD arrangement and specification, based on equipment immunity, insulation, and on SPD energy level coordination. Some results related to electric and electronic system protection are shown and discussed.

II. Methodology for SPD Coordination

Besides the complexity of electrical systems, the selection of SPD considers several parameters, such as surge waveforms, its magnitude and associated energy, frequency of occurrence and origin, equipment immunity level, equipment basic insulation level (BIL), etc. It can lead us to a time consumer design procedures, representing a practical engineering constraint. Then, a suitable and accurate procedure is required to properly define the SPD arrangement and specification. Fig. 1 presents the flowchart with the recommended steps proposed to optimize the SPD selection and coordination.

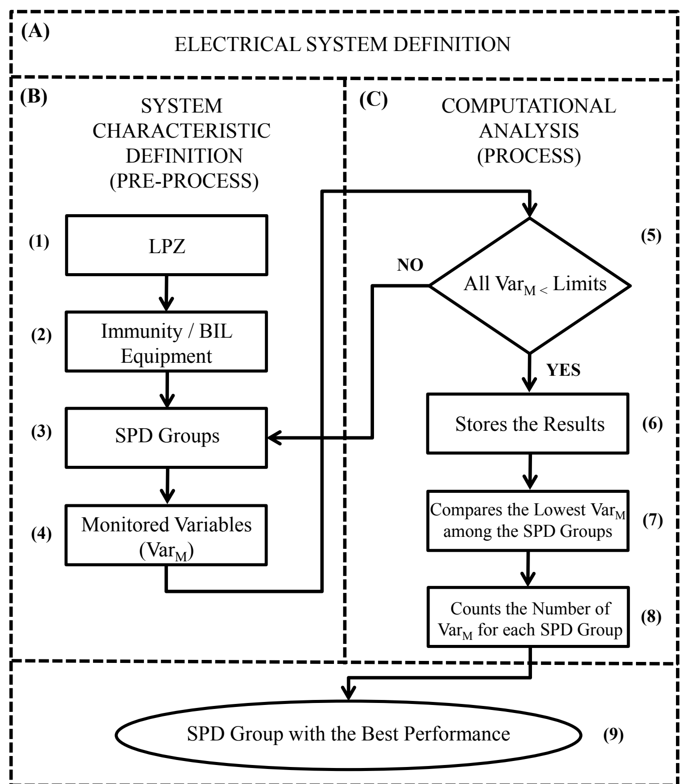

Fig. 1. Criteria flowchart for selecting a coordinated SPD system.

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A. *Electrical System Definition*

The system configuration to be protected, that includes the equipment and the related rated voltages, is taking into account at first step.

B. *SPD Coordination Methodology – Pre-process*

The pre-processing of the SPD coordination methodology is based on the following guidelines:

1) Evaluation of the electromagnetic environment: The Lightning Protection Zones (LPZ) are defined and the lightning parameters like surge waveforms and surge intensities are assigned. Recommendations of international standards can be used in this step [5][6].

2) Definition of the equipment immunity level and equipment BIL, based on designing experience and international standards [7][8].

3) The SPD specification: The probability of surge occurrence, and SPD parameters, such as energy absorption capability; maximum supportable current; operating voltage; and clamping voltage are considered. Manufacturer data sheet and standards recommendations are taking into account [9]. The following criteria applies: a) The SPD operating voltage must be higher than the rated voltage of the electrical system; b) The maximum SPD current withstand must be higher than the peak value of the expected LPZ surge current; c) The maximum SPD clamping voltage should be less than the equipment immunity level and equipment BIL; and d) SPD absorbed energy must be less than the SPD energy capability [10].

4) The monitored variables are the overvoltage across equipment terminals and the current and absorbed energy by SPD. These variables values must be lower than the equipment and SPD limits.

C. *SPD Coordination Methodology – Computational Process*

The SPD model parameters and their arrangements are chosen by applying an iterative process using MATLAB [11] and ATP [12]. The following steps should be performed:

5) It is checked whether all the monitored variables are below the admissible limits for a given SPD group. If yes, it goes to step 6, otherwise, it returns to step 3 and a new SPD group should be assigned.

6) It stores the system response for that SPD group.

7) For each monitored variable, it is pre-selected the SPD group with the lowest values.

8) It counts the number of monitored variables that represents the best result for each SPD group.

9) Finally, based on previous steps, it is selected the best performing SPD group.

Further information on how the interactive process works between MATLAB [11] and ATP [12] can be checked on the reference [13].

III. Application & Results

A sketch of an electrical system branch, similar to industrial and nuclear plant ones, is represented in Fig. 2, and considered as the system to be protected.

The LPZ1 and LPZ2 are the protected zones that are related to the three-phase 480 V and 220 V low voltage bar systems, respectively. As a first approach, two surge attached points are assumed: One on each low voltage bar system. The current surge is assumed as an 8/20μs waveform with 25 kA amplitude for 480 V system, and 10 kA amplitude for 220 V system. These values are chosen based on [5][6].

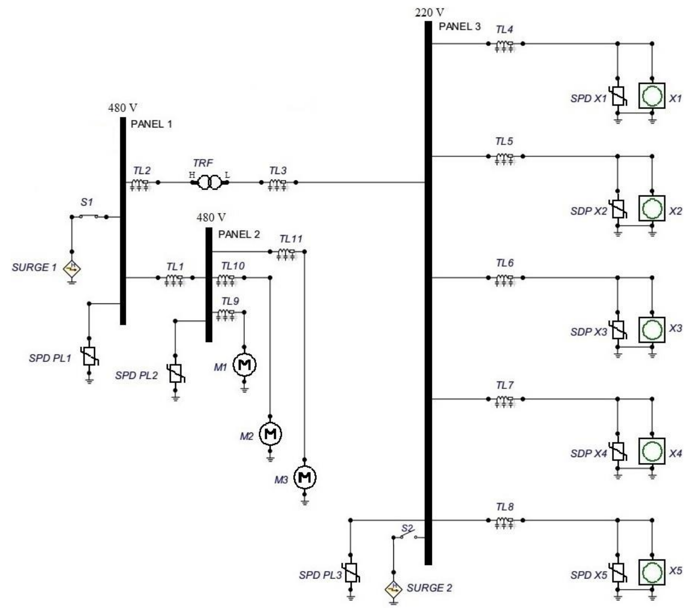

Fig. 2. Electrical system to be protected.

Where:
M: Motors (M1-M3);
S: Switch related to surge injection points (S1 and S2);
TL: Transmission Line (TL1-TL11);
TRF: Transformer;
X: Sensitive Equipment (X1-X5).

The sensitive equipment and the transformer are represented by RLC circuit models [14][15]. Table I gives the cable parameters, these were calculated by a TL tool of ATP using electrical cable constructive characteristics [12]. Table II shows the equipment immunity levels and the BIL.

TABLE I
Power Cable Characteristics

Cable	Section	L (m)	R (mΩ/m)	Z_0 (Ω/m)
TL1	# 300mm2	10	0.045	16.34
TL2	# 185mm2	10	0.071	17.38
TL3	# 2x150mm2	50	0.086	17.53
TL4	# 2.5mm2	10	5.41	43.19
TL5	# 2.5mm2	30	5.41	43.19
TL6	# 2.5mm2	50	5.41	43.19
TL7	# 6mm2	20	2.41	37.55
TL8	# 6mm2	40	2.41	37.55
TL9	# 50mm2	30	0.26	22.11
TL10	# 50mm2	50	0.26	22.11
TL11	# 50mm2	100	0.26	22.11

TABLE II
EQUIPMENT IMMUNITY LEVELS AND BIL

Equipment	BIL	Immunity
Panel 1	12 kV	-
Panel 2	12 kV	-
TRF (H/L)	12/10 kV	-
Motors	4 kV	-
Panel 3	8 kV	-
Sensitive Equipment	-	500 V

The pre-selected SPD groups are presented in Table III, and their respective characteristics in Table IV. All SPD are MOV (Metal Oxide Varistor).

TABLE III
PRE-SELECTED SPD GROUPS

Group	SPD PL1	SPD PL2	SPD PL3	SPD X1-X5
1	B60K320	B60K320	B32K150	S10K150
2	B60K320	B60K320	B32K250	S10K250
3	B60K550	B60K550	B32K150	S10K150
4	B60K550	B60K550	B32K250	S10K250

TABLE IV
SPD CHARACTERISTICS

SPD	V_{RMS} (V)	I_{MAX}(A)	E_{MAX}(J)
B60K550	550	70000	1500
B60K320	320	70000	1000
B32K250	250	25000	330
B32K150	150	25000	240
S10K250	250	2500	38
S10K150	150	2500	24

In the system, the monitored variables are overvoltage on the equipment (13 Var_M), maximum current drained (8 Var_M), and maximum energy absorbed (8 Var_M) by the SPD, totalizing 29 monitored variables.

A. System without using SPD

Firstly, It will be presented the results related to surge on 480 V bar, without SPD. The results alert to the possible hazards and associated damages that a low-voltage electrical system might be subject to. To illustrate, Fig. 3 presents the overvoltage on panel 1, panel 2 and transformer (H) on the 480 V side; and in Fig. 4 are shown the overvoltages on sensitive equipment on the 127 V system (one-phase).

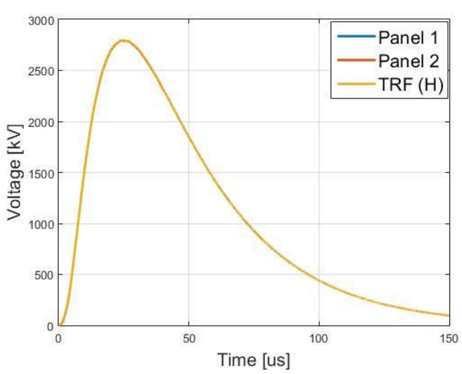

Fig. 3. Overvoltage on the 480 V system equipment.

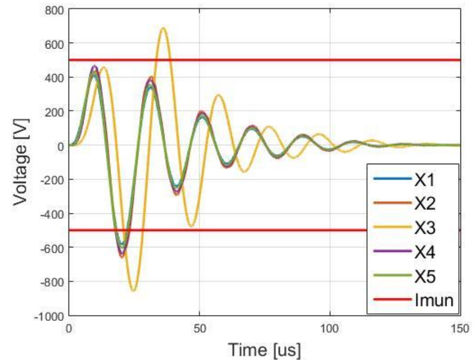

Fig. 4. Overvoltage on the sensitive equipment (X_i).

In Fig. 3 notice the overvoltage on 480 V system equipment reached values close to 2.75 MV that are well above the equipment BIL given in Table II.

B. System with SPD

Fig. 5 shows the results regarding the SPD combinations, assuming Surge 1. It can be realized that SPD Group 2 presents the best performance, reaching 55 % of the best results for the monitored variables. It is important to note that the four SPD groups kept all monitored variables below the limits.

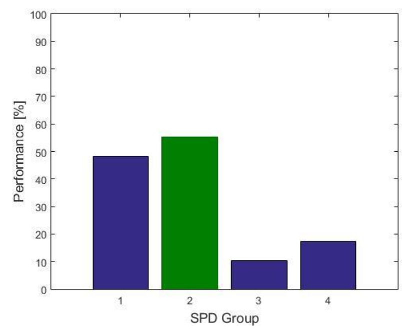

Fig. 5. SPD group performances - surge on the 480 V bar.

It should be noted that, for some monitored variables, the performance levels are the same and, for this reason, the sum of the SPD groups' performance exceeds 100%.

Fig. 6 – Fig. 9 are related to the SPD Group 2 arrangement, showing the resulting current and energy absorbed by SPD on 480 V side, as well as the overvoltage on all equipment of the electrical system (480 V and 220 V).

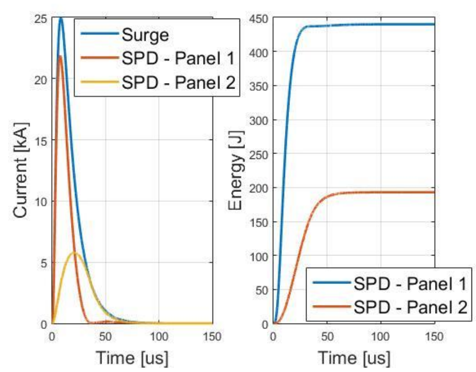

Fig. 6. Current and energy absorbed by SPD of panel 1 and 2.

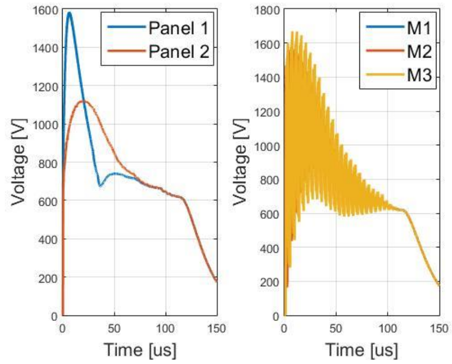

Fig. 7. Overvoltage on panel 1, panel 2 and motors (M_i).

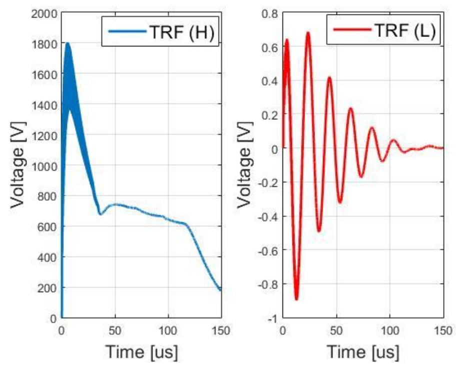

Fig. 8. Overvoltage on transformer.

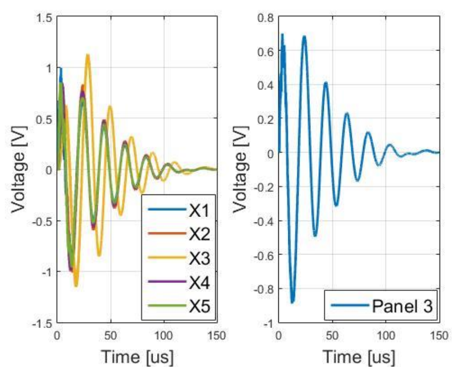

Fig. 9. Overvoltage on sensitive equipment (X_i) and panel 3.

Once considered the Surge 2 injected on 220 V bar, only SPD Group 1 and SPD Group 3 has kept all monitored variables below the limits. The SPD Group 1 has presented the best performance, being more efficient reaching 80 % as showing in Fig. 10.

The clamping voltages of the SPD Group 2 and SPD Group 4 were not compatible with the sensitive equipment immunity levels. Thus, there was also no good energy coordination between the suppressors (SPD near sensitive equipment) and the SPD applied on panel 3.

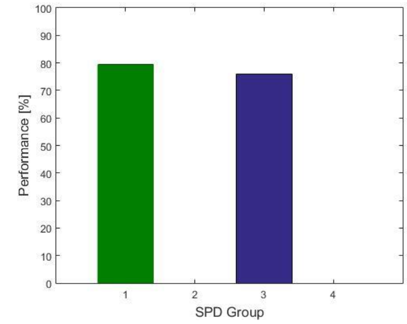

Fig. 10. SPD group with the best performance - surge on the 220 V bar.

Fig. 11 – Fig. 15 present the results related to the SPD Group 1 arrangement, assuming Surge 2, showing the resulting current and energy absorbed by SPD on 220 V side, as well as the overvoltage on all equipment of the electrical system (480 V and 220 V).

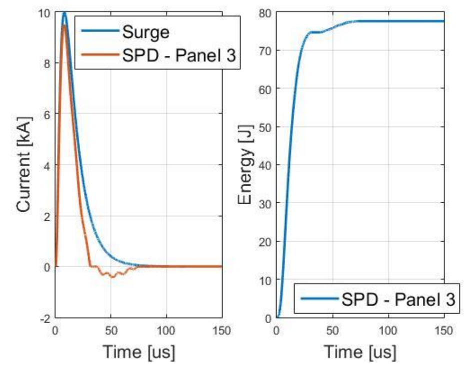

Fig. 11. Current and energy absorbed by SPD of panel 3.

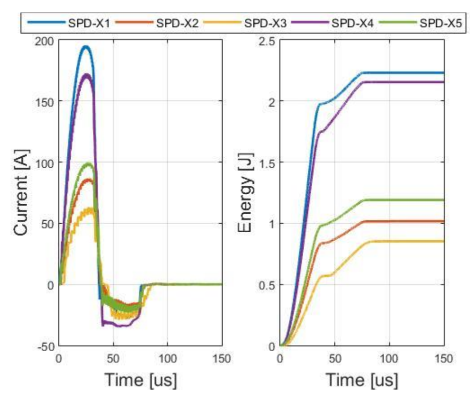

Fig. 12. Current and energy absorbed by SPD of sensitive equipment (X_i).

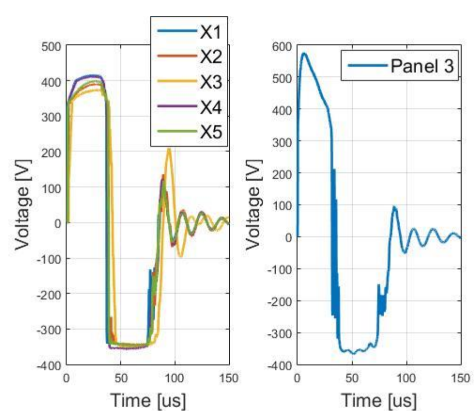

Fig. 13. Overvoltage on sensitive equipment (X_i) and panel 3.

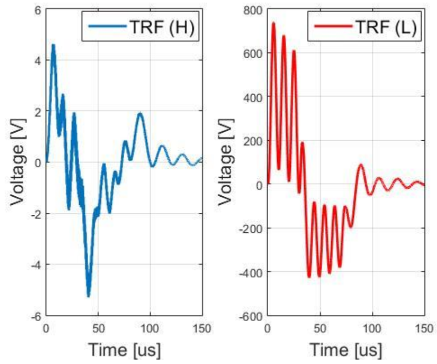

Fig. 14. Overvoltage on transformer.

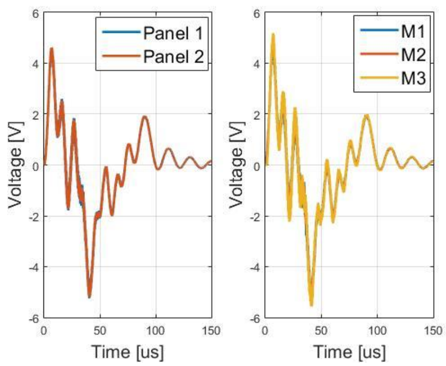

Fig. 15. Overvoltage on panel 1, panel 2 and motors (M_i).

In the illustrations, oscillatory overvoltage on the equipment are stressed. These oscillations can be justified due to the RLC characteristics of the system, and TL wave reflection. It could be realized during previous studies in which parameters like cable length, the load model, etc. were adopted.

SPD Group 1 presented the best global performance, being reaching 64% of efficiency for the monitored variables (Fig. 16).

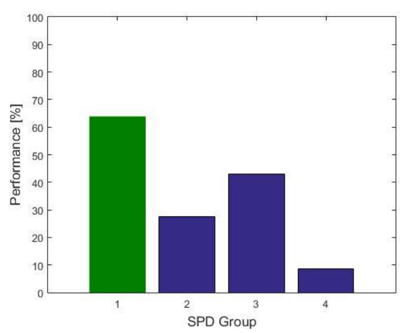

Fig. 16. SPD group with the best global performance.

It was verified that the low clamping voltage and the suitable energy absorption capability of the SPD Group 1 contributed to stand out among the other groups. In this way, it was possible to keep the voltage on the equipment as low as possible, as well as to maintain the integrity of the SPD when these are subjected to the foreseen surges for the system.

IV. Conclusion

The SPD coordination approach used in this work allows, thanks to the integrated use of ATP and MATLAB, resulting in a powerful tool regarding optimization studies of SPD arrangement and specification.

The selected and presented results emphasize the importance of a proper low-voltage SPD coordination methodology since this kind of optimization study depends on many parameters such as types and characteristics of SPD, cable arrangements and their parameters, types of load, etc. It is important to note that there is no single reason why one SPD group stood out in relation to another due to the amount of variables and their combinations.

Concerning installations in which possible failures and malfunctions can affect directly the aspects related to EMC functional safety, like in nuclear plants, studies applying similar methodologies assume an important role.

In future works should be performed system modeling that takes into account the grounding impedance and its type, making the study for optimized solutions more robust. Besides the technical parameters, other ones, related to the economic aspects, should also be taken into account.

References

[1] SRETEN, S. VLADAN, R. “Optimization and Protective Distance of Surge Protective Devices in Low-Voltage AC Circuits,” *46th International Universities' Power Engineering Conference,* Sep. 2011.
[2] JANG, H. S. KIM, B. R. LEE, S. K. “Efficiency and Probability Analysis of Lightning Protection System at Korean Nuclear Power Plant,” *46th International Universities' Power Engineering Conference,* Sep. 2011.
[3] Technical Basis for Regulatory Guidance on Lightning Protection in Nuclear Power Plants, NUREG/CR-6866, 2006.
[4] LAI, J. S. MARTZLOFF, F. D. “Coordinating Cascaded Surge Protection Devices: High-Low versus Low-High,” *IEEE Transaction on Industry Application,* vol. 29, n. 4, Aug. 1993.
[5] Proteção Contra Descargas Atmosféricas – Parte 1: Princípios Gerais, ABNT NBR 5419-1, 2015.
[6] Protection against Lightning - Part 1: General Principles, IEC 62305-1, 2010.
[7] Electromagnetic Compatibility (EMC) – Part 4-5: Testing and Measuring Techniques – Surge Immunity Test, IEC 61000-4-5, 2005.
[8] Insulation Coordination for Equipment within Low-Voltage Systems – Parte 1: Principles, Requirements and Tests, IEC 60664-1, 2007.
[9] Low-Voltage Surge Protective Devices – Part 11: Surge Protective devices connected to low-voltage power systems – Requirements and Test Methods, IEC 61643-11, 2011.
[10] Low-Voltage Surge Protective Devices – Part 12: Surge Protective devices connected to low-voltage power systems – Selection and Application Principles, IEC 61643-12, 2008.
[11] MATLAB software, The MathWorks Inc, 2015.
[12] ATP software, ATPDRAW User’s Manual version 5.6, 2009.
[13] BORSOI, S. S. “Coordenação de Dispositivos de Proteção Contra Surtos em Baixa Tensão - Ênfase Instalações Nucleares,” M.S. dissertation, Dept. Elect. Eng. University of São Paulo, São Paulo, Brazil, 2017.
[14] BASSI, W. “Characterization of low voltage residential equipment and installations applied to the study of atmospheric origin transients,” Ph.D. dissertation, Dept. Elect. Eng. University of São Paulo, São Paulo, Brazil, 2005.
[15] KANASHIRO, A. G. “Distribution transformers Modeling for high frequencies,” Ph.D. dissertation, Dept. Elect. Eng. University of São Paulo, São Paulo, Brazil, 2005.