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Effect of the integration path on the grounding impedance measurement at high frequency

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***Abstract*—This paper discusses the effect of the integration path of the electric field on the grounding impedance measurement at high frequency. It is shown that the integration path is not relevant for low frequencies, as the value yielded by the field integration is close to the one provided by the difference of potential of the electrode with respect to a remote ground. However, the integration path becomes significant for high frequencies, due to the presence of non-conservative electric fields. It is shown that, for the example considered, significant differences appear for frequencies beyond 20 kHz. It is also shown that the configuration of the grounding electrodes may influence the impedance obtained from integrating the electric field. Finally, the paper discusses the challenges in measuring grounding impedances at high frequencies, including the establishment of standing waves on the grounding electrodes and the effect of scattered voltages induced in the measuring wires.**

Keywords—grounding; potential; electric field; high-frequency.

I. INTRODUCTION

The grounding impedance of electric power systems installations is usually assessed at low-frequency, typically around power frequency (50 Hz - 60 Hz). In this frequency range, the grounding impedance is essentially resistive, with an inductive component becoming noticeable only for very large and interconnected grounding grids [1]. Even for low-frequency measurements, several problems need to be mitigated.

For instance, Ma and Dawalibi [2] showed that the self and mutual inductances of the measuring wires may interfere with the measurement. Mitigation techniques to this problem were proposed by Wang et al. [3], which routed the wires to minimize the coupling. Alternatively, Kostic and Raicevic [4] used high direct currents (DC) in the measurements, in order to avoid polarization effects on the electrodes. More recently, Hu *et al*. [5] proposed an interesting technique that measures the mutual inductance between the measuring wires and compensate its effects on the measured grounding resistance.

Ground stray currents may also interfere with the measurement of grounding resistances, and several authors proposed techniques to avoid this interference. For instance, Kostic and Racevic [6] and Griffiths *et al*. [7] used different methods based on variable frequency, whereas Zhou *et al*. [8] proposed an interesting method that injects a current into the ground to cancel the stray currents.

Most of grounding impedance measurements are based on ground surface potentials, which can be affected by the presence of soil non-homogeneities and buried conductors. In an attempt to mitigate this effect, Raizer *et al*. [9] proposed a polynomial regression of the surface potential data, where the effects of soil non-homogeneities are compensated. Recently, Caetano *et al*. [10] developed a new method that is based on the net charge drained by grounding system [11], i.e., the measurement does not rely on the measurement of surface potentials.

As seen, the grounding impedance measurement presents challenges even at low frequency. As the measurement is carried out at high frequency, the number of challenges is expected to increase. This is the case of grounding impedance measurements associated with lightning, where impulsive currents are often used. In this type of measurements, the location of auxiliary electrodes and measuring wires are usually kept as in the traditional low-frequency measurements [12]-[16]. However, the presence of non-conservative fields makes the overall situation more complex, where the measured voltage has some dependence with integration path considered for the electric field. For very high frequencies, even the propagation effects of the scattered voltages along the measuring wires plays an important role on the impedance registered by the measuring instrument.

This issue was investigated by Panicali and Verde [17], which showed that the resulting voltage measured by a grounding meter can be significantly dependent on the integration path, especially its relative position with respect to the grounding electrodes. Despite of the relevance of this subject, it seems to be largely ignored by parts of the scientific community, which continues to evaluate the grounding impedance based only on the scalar potentials, i.e., ignoring the effects of the vector potential on the measuring wires.

One exception is the work carried out by Sunjerga *et al*. [18], which evaluates the path-dependent voltage effects on the measurement of grounding impedance for lightning studies. The authors concluded that, up to a frequency of about 100 kHz, the voltage, and consequently the evaluated impedance, are independent of the path of integration.

However, an analysis of their paper shows that the authors compared the results of two integration paths that are very similar to each other. Indeed, the two integration paths considered have the same length and direction, differing only 0.85 m in height. Obviously, if the paths are close to each other, the differences in the resulting voltages are reduced.

This paper is intended to shed some light on this subject, by comparing the impedance measured for a simple grounding system, considering quite different paths for the voltage measuring wire. The paper is organized as follows: Section II describes the configuration of the considered grounding system and the proposed integration paths, whereas Section III presents the simulation results. Section IV discusses the relevant issues raised by the paper and Section V draws the main conclusions.

II. GROUNDING SYSTEM CONSIDERED

In order to study the effect of the integration path on the grounding impedance measurement at high frequency, it is considered the grounding system shown in Fig. 1.a. This grounding system is typically used at the towers of overhead power transmission lines, whereas the parallel sections follow the line right-of-way. The electrodes are buried at 0.5 m deep and have 7 mm radius.

It is relevant to note that this grounding system is not symmetrical with respect to the azimuthal angle α, defined as a counterclockwise angle as shown by the blue lines in Fig. 1.a. This azimuthal asymmetry is likely to enhance the effect of the integration path, as will be shown in the following. By comparison, the vertical rod used by Sunjerga *et al.* [18] has azimuthal symmetry, which reduces the influence of the integration path.

Fig. 1.b. shows the different integration paths considered, which are denoted by red lines and defined by different values of α, namely: α = 0°, 45°, and 90°. In all cases, the current is injected vertically at the midpoint of the grounding system and the voltage is integrated from the midpoint up to 120 m away. The calculation is carried out in frequency domain using several frequencies from 10 Hz to 5 MHz.

III. SIMULATION RESULTS

The results shown in this section were computed with the Tragsys Computer Software [19], which is dedicated to the grounding system analysis. It is a computer software designed for analysis of low and high frequency, as well as the transient behavior of grounding structures. It uses a rigorous mathematical formulation derived from the complete set of Maxwell's equations, numerically solved by the method of moments (MoM).

The calculations are carried out in frequency domain and the relation of the results with the currents associated to lightning flashes is discussed in Section IV.

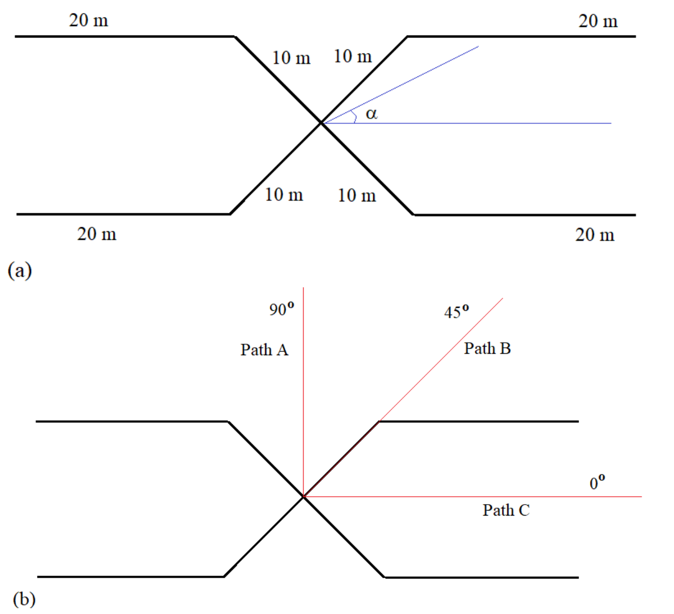

Fig. 1. Grounding system considered for the simulations. (a) Dimensions and definition of α; (b) Three different integration paths considered.

The grounding system impedance is defined as the ratio between the voltage developed in the grounding system to the injected current. The injected current can be precisely defined and measured, as it is the current that flows in the conductor that connects the generator to the grounding system. The resulting voltage, however, cannot be uniquely defined, except for the case of direct current (DC) or, as an approximation, in the case of low frequency. This condition corresponds to the assumption that the measuring wires are subjected only to conservative fields, so that the voltage between the grounding system and a remote point at the ground surface does not depend on the path described by the voltage measuring wire. This is the case where only the scalar potential is relevant.

However, if high frequencies are considered (as in the problems concerned with lightning flashes), the electric field around the electrodes is non-conservative, so that the measured voltage becomes path-dependent. In order to illustrated this, the voltages obtained by integrating the electric field along the direction of the measuring wires shown in Fig. 1.b are computed. The integration path is straight and follows the ground surface (assumed as plane), remembering that the grounding electrodes are buried at 0.5 m. The electric field integration is performed from the grounding electrode midpoint up to a point at ground surface 120 m away. Two sets of ground relative permittivity (ε_r) and resistivity (ρ) are considered: $\varepsilon_r = 10$ and $\rho = 100\ \Omega\cdot$m for one case and $\varepsilon_r = 5$ and $\rho = 1000\ \Omega\cdot$m for the other case.

Fig. 2 shows the results obtained considering the 100 Ω·m ground resistivity value, for the three paths described in Fig. 1. This figure also shows the impedance Z that is calculated considering only the scalar potential, i.e., dividing the potential of the electrode midpoint by the injected current.

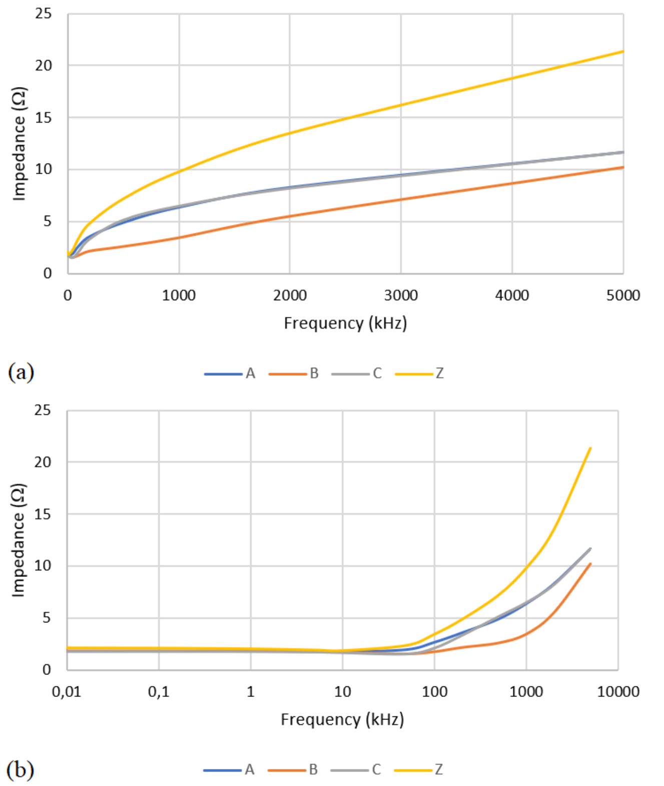

Fig. 2. Impedances calculated from the integral of the electric field along the paths A, B, and C shown in Fig. 1.b for 100 Ω·m ground resistivity. Z is the impedance obtained considering only the scalar potential; (a) Linear frequency axis; (b) Logarithm frequency axis.

It can be seen in Fig. 2 that the three paths and the scalar potential yield approximately the same values of impedance for low frequencies, as expected. However, beyond 20 kHz the curves start to spread, with the impedance from the scalar potential increasing faster with frequency. For the higher frequency range, the integration path B provides always the lower impedance values. This is likely because this path runs close to one electrode and that the axial electric field along the electrode surface is null. Therefore, path B receives some shielding from the grounding electrode, especially in the region where the electric fields are more intense (i.e., near the current injection point).

Interestingly, the path A and C provide impedance values that are close to each other. This could be explained by considering that these paths are relatively far from the grounding electrodes (comparing with path B), and have similar exposition to the grounding electrodes for the first 7 m. Therefore, the influence of the electrode sections parallel to path C on the integrated field seems to be negligible.

The impedance from the scalar potential (Z), by its turn, is always higher than the others. This value is calculated neglecting the effects of the vector potential that, in general, tends to partially cancel the effects of the scalar potential. Therefore, the higher values of the impedance based on the scalar potential are expected. Finally, it is worth to mention that this quantity is purely theoretical, as any attempt to measure it requires laying measuring wires that would be subjected to the inducing electromagnetic fields.

Fig. 3 shows the results obtained considering the 1000 Ω·m ground resistivity value, for the three paths described in Fig. 1. This figure also shows the impedance Z that is calculated considering only the scalar potential, i.e., dividing the potential of the electrode midpoint by the injected current. For the low frequency range, the three paths provide approximately the same impedance value, as expected. However, the impedance Z calculated from the scalar potential is slightly higher than the values yielded by the integration of the electric field. This could be explained by the size of the segments used in the numerical integration close to the current injection point.

With increasing frequencies, the impedances drop slightly at about 200 kHz. After this point, the impedance based on the scalar potential (Z) raises steadily, while those based on the integration of the electric field stay together up to about 1 MHz, when they spread. The behavior of the impedances above 1 MHz is likely due to the establishment of standing waves in the grounding electrodes for these frequencies.

Similarly to the case of 100 Ω·m ground resistivity, path B provides always the lower impedance values. However, in this case a clear distinction is observed between the impedances provided by paths C and path A, with path C showing lower values. This can be explained by considering that, for the relatively high value of ground resistivity considered in this case (1000 Ω·m), the currents on the electrode sections parallel to path C is no longer negligible. This would provide a higher shielding to path C than to path A, justifying the lower impedance values of the former.

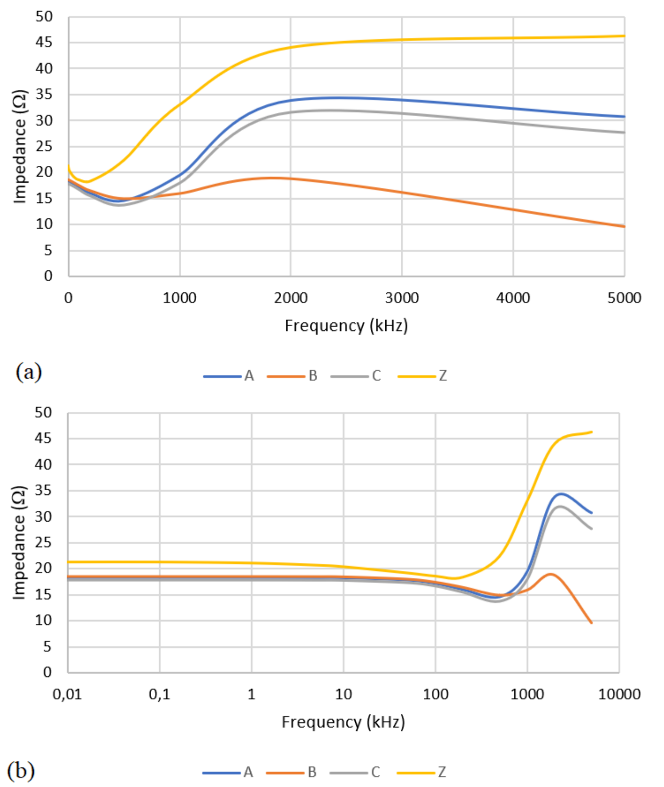

Fig. 3. Impedances calculated from the integral of the electric field along the paths A, B, and C shown in Fig. 1.b for 1000 Ω·m ground resistivity. Z is the impedance obtained considering only the scalar potential; (a) Linear frequency axis; (b) Logarithm frequency axis.

As expected, the impedance from the scalar potential (Z) is always greater than the others. However, differently from Fig. 2, where the impedance curves start to diverge beyond about 20 kHz, in Fig. 3 they start to diverge beyond about 200 kHz.

From the results shown in Figs. 2 and 3, it is clear that the grounding system impedance cannot be uniquely defined for the high-frequency region. Indeed, depending on the integration path, different impedance values can be assessed. This issue is discussed in the next section.

IV. Discussion

Section III showed that the grounding impedance can be uniquely defined for low frequency, whereas it attains the value yielded by the scalar potential. However, for high frequencies, the grounding impedance cannot be uniquely defined, because the voltage obtained by integrating the electric field is path dependent.

At this point, it is important to highlight that, in order to measure any voltage between the grounding electrode and a remote point, it is necessary to lay a measuring wire between these points. In this case, the electric field will act along this wire and induced scattered voltages that travel along the wire. This is the same phenomena considered in the calculation of lightning induced voltages in aerial lines [20]-[23].

If low frequency is considered, these propagation effects can be neglected and a voltmeter inserted in the measuring wire will provide the scalar potential of the electrode, which is also independent of the path of the measuring wire. For high frequency, however, propagation effects are likely to influence the measured voltage and, consequently, the measured impedance. Therefore, the grounding impedance measurement using high frequency must take into account not only the route of the measuring wire (integration path), but also the propagation effects arising on it.

The only way to have a uniquely defined grounding impedance at high frequency seems to define, a priori, the configuration used by the measuring wires. However, this configuration must be related to the practical application of the measured value, where a voltage of interest (e.g., across an insulator or at the input port of an equipment) is related to the exciting current. In other words, in a system composed of distributed parameters, it seems that is not possible to define a unique impedance at high frequency. On the other hand, it is possible to uniquely define a transfer impedance, which relates a specific voltage to the corresponding exciting current.

The examples presented in this paper were calculated in frequency domain, whereas the application of grounding impedance measurement is usually related to lightning. Therefore, it is relevant to analyze the frequency spectrum of lightning flashes. Fig. 4, reproduced from IEC 62305-1 [24], shows the current density (A / Hz) along the frequency range. It can be seen that the current intensity falls monotonously with increasing frequency, but significant content is present up to 1 MHz, especially for subsequent strokes. Therefore, as long as lightning flashes are concerned, the grounding impedance measurement should cover such frequency range.

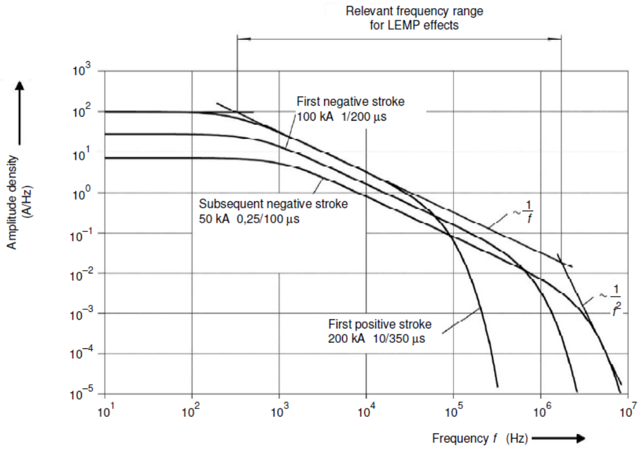

Fig. 4. Distribution of the lightning curent along the frequency spectrum, for the first positive stroke, first negative stroke and subsequent negative stroke. Adapted from IEC 62305-1 [24].

V. Conclusion

The grounding impedance measurement at high frequencies is likely to be influenced by the path considered for the integration of the electric field, as it may be influenced by the configuration of the grounding electrodes. This electric field integration is normally carried out by a voltage measuring wire, which is connected between the grounding system and a remote point at ground surface. Therefore, due to the presence of non-conservative electric fields, the voltage measured by an instrument connected to the wire may be quite different from the potential of the electrode. The aim of this paper is to call the attention to this fact is to encourage further research on this field. Hopefully, the development of theoretical and experimental work on this subject may yield to a consistent definition for the grounding system impedance.

References

[1] IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding, IEEE Std. 81-2012, Dec. 2012.

[2] J. Ma and F. Dawalibi, "Influence of inductive coupling between leads on ground impedance measurements using the fall-of-potential method," *IEEE Trans. Power Del*., vol. 16, no. 4, pp. 739-743, Oct. 2001.

[3] C. G. Wang, T. Takashima, and T. Sakuta, and Y. Tsubota, "Grounding resistance measurement using fall-of-potential method with potential probe located in opposite direction to the current probe," *IEEE Trans. Power Del*., vol. 13, no. 4, pp. 1128-1135, Oct. 1998.

[4] V. I. Kostic and N. B. Raicevic, "A study on high-voltage substation ground grid integrity measurement," *Electric Power Syst. Res*., vol. 131, pp. 31-40, Feb. 2016.

[5] Z. Hu, S. Ni, B. Zhang, and K. Zhang, "New method of measuring ground impedance and mutual impedance between measuring lead wires," *IEEE Trans. Power Del*., in print.

[6] V. I. Kostic and N. B. Raicevic, "An alternative approach for touch and step voltages measurement in high-voltage substations," *Electric Power Syst. Res*., vol. 130, pp. 59-66, Jan. 2016.

[7] H. Griffiths, P. Jones, N. Harid, and A. Haddad, "Proposal for measurement of earth impedance using variable frequency injection," *Meas. Sci. Technol*., vol. 21, no. 8, pp. 1-8, p.085102, 2010.

[8] W. Zhou, Y. Liu, G. Li, G. Yan, S. Yang, H. Li, C. Zhou, and C. Q. Su, "Power frequency interference and suppression in measurement of power transmission tower grounding resistance," *IEEE Trans. Power Del*. vol. 30, no. 2, pp. 1016-1023, April 2015.

[9] A. Raizer, W. Valente, and V. L. Coelho, "Development of a new methodology for measurements of earth resistance, touch and step voltages within urban substations," *Electric Power Syst. Res*., vol. 153, pp. 111-118, Dec. 2017.

[10] C. E. Caetano, J. O. S. Paulino, C. F. Barbosa, J. C. O. Silva, A. R. Panicali, "A new method for grounding resistance measurement based on the drained net charge", IEEE Transactions on Power Delivery, vol. 34, n. 3, pp. 1011-1018, June 2019.

[11] J. C. O. Silva, A. R. Panicali, C. F. Barbosa, C. E. F. Caetano, J. O. S. Paulino, "Electric charge flow in linear circuits", Electric Power Systems Research, vol. 170, pp. 57-63, May 2019.

[12] S. Visacro and G. Rosado, "Response of grounding electrodes to impulsive currents: An experimental evaluation", IEEE Trans. on Electromagn. Compatibility, vol. 51, no. 1, pp. 161-164, Feb. 2009.

[13] A. B. Lima, C. E. F. Caetano, J. O. S. Paulino, W. C. Boaventura, I. J. S. Lopes, C. F. Barbosa, "An original setup to measure grounding resistances using fast impulse currents and very short leads", Electric Power Systems Research, vol. 173, p. 6-12, Aug. 2019.

[14] A.B. Lima, et al., Transient grounding impedance and transient resistivity measurements using a very short current lead, Electr. Power Syst. Res. 118 (January) (2015) 69–75.

[15] W.A. Chisholm, E. Petrache, F. Bologna, Comparison of low frequency resistance and lightning impulse impedance on transmission towers, International Symposium on Lightning Protection (X SIPDA), Curitiba, Brazil, 9th–13th November, 2009.

[16] S. Visacro, R. Alipio, M. H. Murta Vale, and C. Pereira, "The response of grounding electrodes to lightning currents: The effect of frequency-dependent soil resistivity and permittivity," IEEE Trans. Electromagn. Compat., vol. 53, no. 2, pp. 401–406, May 2011.

[17] M. A. S. Verde and A. R. Panicali, "Dynamic behaviour of grounding systems subjected to impulsive signals", VIII Int. Symp. on Lightning Protection, Sao Paulo, Brazil, Nov. 2005.

[18] A. Sunjerga, D. S. Gazzana, D. Polyak, H. Karami, K. Sheshyekani, M. Rubinstein, and F. Rachidi, "Tower and path-dependent voltage effects on the measurement of grounding impedance for lightning studies", IEEE Trans. Electromagn. Compat., vol. 53, no. 2, pp. 401–406, May 2011.

[19] Tragsys Computer Software, www.tragsys.com, accessed 10 June 2019.

[20] J. O. S. Paulino, C. F. Barbosa, I. J. S. Lopes, W. C. Boaventura, G. C. Miranda, "Indirect lightning performance of aerial distribution lines considering the induced-voltage waveform", IEEE Transactions on Electromagnetic Compatibility, v. 57, no. 5, p. 1123-1131, Oct. 2015.

[21] A. Andreotti, V. A. Rakov and L. Verolino, "Exact and approximate analytical solutions for lightning-induced voltage calculations," in *IEEE Trans. Electromagn. Compat*. (in print).

[22] [24] M. E. M. Rizk, F. Mahmood, M. Lehtonen, E. A. Badran, M. H. Abdel-Rahman, "Influence of highly resistive ground parameters on lightning-induced overvoltages using 3-D FDTD method," IEEE Trans. Electromagn. Comp., vol. 58, no. 3, June 2016.

[23] C. F. Barbosa, C. E. F. Caetano, J. O. S. Paulino, "Effect of high-resistivity ground on the lightning performance of overhead lines", Electric Power Systems Research, vol. 172, pp. 253-259, July 2019.

[24] IEC Std. 62305-1, Protection against lightning, Part 1: General principles, Geneva, 2010.

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