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Concerns with Faults to Ground in Wind and Solar Power Plants Implanted in Tropical Areas – The Influence of Underground Cables on the Methods of Neutral Grounding

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Tables 1 and 2 are available in the Supplementary Files section.

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***Abstract*—The significant increase in the implantation of solar and wind power plants, which has been experienced in several countries with tropical latitudes, has raised serious technical concerns for the involved engineering teams. Most of these concerns are related to protection failures when the occurrence of phase(s) to ground faults in the medium-voltage circuits. Specifically, the reported failures arise from the combination of the adopted method for grounding the neutral of the collector transformer and the predominant adoption of underground cables, which capacitance to ground is significantly influent. With the aim to contribute for addressing most of the problems related to the fault detection, this study shows how the choice of the method of neutral grounding plays a decisive role in the correct adjustment of the protective devices. For doing so, this work analyzes three of the most typical and real cases of single-phase fault to ground, in Brazil, with the help of oscillography and computer simulation. The result is that the shared experience can help and motivate engineering teams to develop their own studies with the aid of computer tools, by considering reproducing the presented results as a basis.**

***Key words* — Capacitance, Grounding, Short-circuit currents, Solar power generation, Wind power generation.**

I. INTRODUCTION

Because of climate reasons, many solar and wind power plants have been implanted in areas within the tropical latitudes of several countries, by including Brazil. In turn, most of these plants represent the investment of groups that usually adopt the technical principles of projects of similar plants formerly built in other countries. In this context, the engineering teams involved in these new solar and wind power plants are composed of local engineers who are not familiar with some of those consolidated technical principles, which gives rise to several significant issues to be addressed. Regarding the electrical project, issues are in the correct adjustment of the protective devices, as relays, in the case of the occurrence of faults to ground in the medium-voltage circuits. Specifically, these issues arise from the combination of the adopted method for grounding the neutral of the collector transformer and the predominant adoption of underground cables. On the other hand, most of the local engineers are not familiar with underground, but only with overhead cables. Therefore, the significant influence of the capacitance to ground of the underground cables, in comparison to that of the overhead cables, which is almost negligible, is rather new. Moreover, most of the same engineers are not familiar with other methods of grounding the neutral of a transformer than that known as the solidly grounded one. These facts explain why so many cases of malfunction and /or misoperation of the protective systems of those power plants have yielded demand for consulting services to companies specialized in circuit protection. Especially in Brazil. Thus, to contribute for addressing most of the problems related to the fault detection in both the types of power plants this work is based on

a brief review of the main methods of grounding the neutral of the collector transformer of power plants and analyzes three emblematic cases of fault to ground with the help of oscillography, usually available in digital relays, and computer programs of transient analyses.

Regarding the protection of circuits of a power plant for a single-phase to ground short-circuit, the choice of the method for grounding the power transformer neutral requires considering the constant evolution of the protection techniques and the respective economic viability of the deployable devices before their deployment may occur [1-3]. This statement is significantly important for the MV-Medium-Voltage circuit of solar and wind power plants that have been intensively implanted in countries with areas located in the tropical latitudes. The main reason for this importance is that those solid principles applied by power utilities for grounding the neutral of MV distribution transformers cannot be applied to the MV collector circuit of these plants before a set of studies of adaptive measures is carried out. One of the main reasons for this precaution is the fact that in solar and wind power plants, most of the MV feeders are composed of underground cables with a relatively long length that invariably exceeds 10 km [4]. This characteristic makes the capacitance of each of the phases to ground increase significantly in comparison to the MV feeders with overhead cables, preferentially adopted in most of the power utilities of this Globe area. In consequence, some unusual facts occur in the behavior of a single-phase to ground short-circuit current due to the contribution of the now-significant capacitive component. In some cases, the capacitive component causes an increase in the amplitude of the single-phase to ground short-circuit current that it becomes a concern for the underground cable shielding because of its relatively limited cross-section and consequent low current capacity. On the other hand, in wind and solar power plants, the occurrence of a single-phase to ground short-circuit is the most likely type of short-circuit to occur. Indeed, more than 98 % of the cases, as reported in [5]. Within this scenario, in wind and power plants, some key specific items must be carefully considered in short-circuit analyses for correctly setting the protection systems of their MV circuits. This is especially true in regard to the adopted method for grounding the neutral of the power transformer, known as the collector transformer, located in the collector substation. For this last item, even for the two methods that are mostly adopted, some undesired malfunctions and failures are invariably present and are critical enough to justify the development of deeper analyses in the relaying adjustment. Thus, to contribute to the improvement of the techniques of protection systems deployed in solar and wind power plants, this work presents the analysis of three representative study cases of single-phase to ground short-circuit with protection failure due to inadequate adjustment. Their choice was based on the fact that similar cases have been reported to the authors very frequently, as happening in many of the operating plants spread all over the Brazilian territory, located in the tropical area. For properly discussing these three cases, some basic features of wind and solar power plants are introduced, with emphasis on the evaluation of the significant underground cable capacitance and respective shielding current capacity. Yet, a brief review of the main methods adopted for grounding the transformer neutral is presented.

II. Basic Features of Solar and Wind Power Plants

With the aim of enabling the understanding of some specific characteristics of large wind or solar generation plants, the typical configuration of their electric circuits is very similar to that shown in Fig. 1, and it is to be used as a reference from this point on.

FIGURE 1

Fig. 1. Typical configuration of the electric circuit of a wind or solar power plant.

This typical configuration has been largely adopted in power plants located in tropical areas based on projects implemented in the Northern Hemisphere [6]. It consists of a power transmission line for connecting the power grid to the high-voltage side of the power transformer of the collector substation, whereas several feeders convey the power collected from each of the generating units to the MV side of this same transformer. The feeders constitute the MV collector circuit that operates with a voltage ranging from 33 to 35 kV, and it is mostly composed of underground cables with an average length of 10 km [4]. At each of the generating units, there is a transformer that adapts the value of the generation voltage from about 600 V to the MV side [5].

When in each of these power plants an unavoidable short circuit to ground occurs, the influence of the adopted method for grounding the collector transformer neutral becomes decisive for the effective clearing of the fault. Thus, because of the importance of this item, it deserves a review that is performed in the sequence.

III. Brief Review of the Methods for Grounding the Neutral of a Transformer

The methods for grounding the neutral of a transformer represent one of the most important issues in power systems because of the stability and safety it must provide in the unavoidable case of occurrence of a short-circuit to ground fault [7]. These methods are divided into three types [8,9]. Namely, the isolated, the solidly grounded, and the grounded by impedance. Fig. 2 shows the respective diagrams of these three methods when applied to the MV side of the collector transformer. In turn, the method of neutral grounding by an impedance has two types that are with the insertion of an impedance itself and with the adoption of a zig-zag transformer.

FIGURE 2

Fig. 2. Diagram of the methods of transformer neutral grounding.

The method of the neutral isolated gives origin to significant transient overvoltage when a fault to ground occurs, because of electric arcs and reignition [10]. Thus, since this is the most frequent type of fault, its associated overvoltage and arcs are the biggest disadvantages of this method, along with these additional disadvantages [10,11]:

- Clearance of any fault requires complex protection measures;
- Precise fault location is not an easy task;
- The insulation cost of the involved equipment is significant because of the increase in the voltage amplitude of the healthy phases;
- Likely to occur significant ferroresonance.

Because of these disadvantages, the method of isolated neutral is not deployed in the MV side of the collector transformer of solar and wind power plants.

Regarding the method of the neutral solidly grounded, although its name suggests that it corresponds only to the case when the value of the impedance between the neutral of the transformer and the ground is null, it has a broader definition that is the comparison of the value of the ratio of the zero sequence grounding resistance, R_0, to the positive sequence grounding reactance, X_1, along with the value of the ratio of the zero sequence grounding reactance, X_0, to the positive sequence grounding reactance X_1 [1]. Effectively, the neutral of a transformer is considered to be solidly grounded if

$$R_0 / X_1 \leq 1 \text{ and } X_0 / X_1 \leq 3 \quad (1)$$

By meeting this criterion, it enables limiting the amplitude of the voltage to ground of the healthy phases to a maximum of 1.4 times the rated voltage during a frank single-phase to ground short-circuit. On the other hand, it limits the value of the amplitude of the single-phase to ground short-circuit current to be significantly greater than the value of the amplitude of the three-phase short-circuit current [1], which represents a harmful consequence to the power transformer and the cable shielding because of the associated sudden increase in their operating temperature. Thus, whereas power transformers are designed to withstand such a short-circuit current [12], the same is not true for the cable shielding, which requires that its rating must be carefully coordinated with the short-circuit protection in order to avoid unrecoverable damages, such as the metallic shielding fusion. In turn, the values of the cross-sectional area of the metallic shielding of the most commercially available cables and their corresponding maximum values of current amplitude are shown in Table 1, based on the usually adopted values of elapsed time to clear the fault of 0.5 and 1.0 s, during a single-phase to ground short-circuit [14].

TABLE 1

On the other hand, to meet the requirements represented by the values presented in Table 1, in most of cases, it is necessary to insert an impedance for grounding the transformer neutral, which makes the value of the grounding impedance to be out of the range presented in (1). This is a method of neutral grounding that has become very commonly deployed in the MV circuit of solar and wind power plants, and it is analyzed in the next subsection.

A. GROUNDING BY IMPEDANCE

The deployment of an impedance for grounding the neutral of a transformer enables to meeting three important requirements that are limiting the amplitude of the transient overvoltage of the healthy phases to ground, limiting the amplitude of the single-phase to ground short-circuit current, and simplifying the adoption of protective initiatives towards to clearing fault occurrences. In the cases when the transformer neutral is accessible, this impedance is a resistor. On the other hand, in cases when the transformer connection is in delta or even in wye but the neutral is not accessible, a usual alternative is the use of a three-phase reactor with windings connected in zig-zag. Thus, despite being a reactor, it is usually named as a zig-zag transformer or a grounding transformer, and it is its leakage reactance that plays the role of the grounding impedance.

To evidence the differences in adopting a resistor or a zigzag transformer as grounding impedance, Figure 3 shows the behavior of the components of the single-phase to ground short-circuit current when the neutral is grounded by a resistor, in Fig. 3 (upper) and by a zig-zag transformer (lower). The components of the fault current, I_G, are the capacitive current, $3I_{co}$, and the current of the neutral point, I_R, in the case of the use of a resistor, R. In the case of the use of a zig-zag transformer, the components of the fault current, I_G, are the capacitive current, $3I_{co}$, and the current of the neutral point, I_L. In addition, phasor charts with the sum of the involved current components are shown for each of the two methods.

FIGURE 3

Fig. 3. Behavior of the single-phase to ground short-circuit current for the method of neutral grounding by impedance. With a resistor - upper; With a zig-zag transformer - lower.

It is important to mention that the presence of the tertiary winding in Fig. 3(upper) is very frequent in solar and wind power plants. It is intended to reinforce the zero-sequence component of the single-phase short-circuit current to circulate as well as to mitigate overvoltage of the healthy phases to ground, as explained in [15].

In correspondence to Fig. 3, Fig. 4 illustrates the respective circuits of the diagram of sequences [16].

FIGURE 4

Fig. 4. Circuits of the diagram of sequences for the two types of the method of neutral grounding by impedance. Upper - with a resistor and a tertiary winding. Lower - with a zig-zag transformer.

At last, regarding each of the transformers to which each generating unit is connected, shown in Fig. 1, since its windings at the MV side are connected in delta, none of these generating units contributes to a single-phase to ground short-circuit current in the MV collector circuit.

On the other hand, because of the influence of the underground cable capacitance as a key contributing component of the short-circuit current, a deeper analysis of its nature is presented in the next section.

IV. Capacitance of Underground Cables – Evaluation and Influences

Underground cables have a significant capacitance in comparison to overhead cables. Reasons for this rely on the shielding and on the dielectric material between the inner conductor and the shielding itself, as shown in the cross-section of a typical cable, in Fig. 5.

FIGURE 5

Fig. 5. Cross-section of a typical underground cable.

Based on Fig. 5 and by [17], the value of the capacitance of the cable, C_ℓ, is given by

$$C_\ell = \frac{0.0556\epsilon_r}{ln\left[\frac{1+2t}{dc+2eb}\right]} \tag{2}$$

in which ϵ_r is the value of the relative dielectric permittivity of the cable insulation (e.g. 2.3 for XLPE - Cross-linked polyethylene and 3.0 for EPR - ethylene propylene rubber); t is the value of the thickness of the insulating layer, in mm; dc is the value of conductor diameter, in mm, and eb is the value of the shielding thickness, in mm. C_ℓ is in μF/km.

By using (2) with the values of the conductor diameter listed in Table 2 and the usual values for t and eb, it is possible to estimate the value of the capacitance of the usually adopted cables in MV feeders as well as it enables to evaluate the capacitive component of the single-phase to ground short-circuit current, indicated as $3I_{co}$, in Fig. 3 and also listed in Table 2, based on the assumption of the rated voltage of 35 kV, as in [15].

TABLE 2

By taking as reference the average value of the capacitance to ground of an overhead cable as being about 7 nF/km, the value for the capacitance to the ground of underground cables is, on average, significantly greater than it, which makes its influence far from being negligible. For example, and as listed in Table 2, in a typical MV circuit of a wind or solar power plant, the average value of the capacitive contribution is about 6 A per km of the underground circuit whenever a single-phase to ground short-circuit occurs. This important fact fully impacts the protection adjustment, as will be analyzed in the next section.

V. Typical Cases of the Influence ff the Capacitive Component on Single-Phase to Ground Faults in the MV Circuit ff Solar and Wind Power Plants

To illustrate how the capacitive influence of the underground cables occurs, three illustrative cases of single-phase to ground short-circuit in the MV circuit of solar and wind power plants are analyzed. With this aim, consider the adaptation of that same single-phase diagram of Fig. 1 with the addition of the indication of the hypothetical occurrence of a single-phase to ground short-circuit in a feeder labeled as F01, in the MV collector circuit of a wind or solar power plant, as it is schematically presented in Fig. 6.

FIGURE 6

Fig. 6. Single-phase diagram of a wind/solar power plant under the occurrence of a single-phase to ground fault.

These three cases are presented in sequence with the help of practical data obtained from relays usually installed in most of the wind and solar plants, such as oscillography, for example. Moreover, data from computer simulations are also presented to reinforce the analyses through comparison to practical data.

A. Case 1 - Unduly tripping of a healthy feeder circuit

The first case of analysis corresponds to a single-phase to ground fault in phase A of the feeder labeled as F01, as indicated in Fig. 6, and the tripping of its corresponding neutral overcurrent protection does not occur. However, the neutral overcurrent protection of the feeder circuit labeled as F12, and also indicated in Fig. 6, unduly trips instead. This is what is suggested by the oscillography of the voltage and the current of the feeder F12, shown in Fig. 7.

FIGURE 7

Fig. 7. Case 1 – Oscillography of the three-phase voltage and current of feeder F12 during the fault.

Based on this oscillography, it is possible to notice that right after the beginning of the occurrence of the single-phase to ground fault in the adjacent feeder F01, marked by the vertical and red dashed line, no significant disturbance can be noticed in any of the three-phase currents of this feeder, F12. Nonetheless, after about 250 ms, the circuit of the F12 feeder is unduly open and its current is interrupted. On the other hand, over the same time range, the three-phase voltage to the ground of the feeder F12, which is the same voltage as the main busbar of the collector substation, behaves as expected. That is, the amplitude of the voltage to ground of phase A decreases significantly, whereas the voltage to ground of the other two phases, B and C, has a significant increase in amplitude. After the circuit is open, the three-phase voltage of the main busbar returns to its normal condition.

Thus, although the presented oscillography gives evidence that phase A is the faulty one, it does not explain the tripping of the neutral overcurrent protection of the feeder F12. For elucidating this, the oscillography of the neutral current of the healthy feeder F12, is presented for the same period of the fault, in Fig. 8.

FIGURE 8

Fig. 8. Case 1 – Oscillography of the neutral current of the feeder F12.

The presented oscillography shows that the RMS value of the neutral current of the neutral of the F12 feeder reaches 63.6 A, which explains its protection trip since its limit value was set to 50 A. Regarding the reason for such a significant value of current, it is likely that it is due to the capacitive contribution of the underground cables of all the feeders, as indicated in Fig. 3 as $3I_{co}$.

As additional information in this case, the neutral of the transformer collector is grounded by a resistor.

B. Case 2 – The impact of the capacitance of the underground cables on the amplitude of the single-phase to ground short-circuit current

The second case also corresponds to several real cases of fault to ground in feeders of solar and wind power plants. However, those real cases when the transformer neutral is grounded by a zig-zag transformer at the MV side. Thus, consider the same faulty feeder labeled as F01 in Fig. 6 and its oscillography, shown in Fig. 9.

FIGURE 9

Fig. 9. Case 2 – Oscillography of voltage and current of the feeder F01 during the fault.

It is interesting to notice in the presented oscillography that the three-phase voltage of the whole plant goes to zero after a time interval is elapsed with a short-circuit fault of phase C, which is evidenced by the behavior of the three-phase voltage. This voltage clearing means that the neutral relay of the zig-zag transformer caused the protection trip, in a backup condition to the relay of the faulty feeder F01. Nonetheless, the current of phase C does not show a significant increase in its amplitude during the fault, but behaves in a non-regular way, with noticeable peaks of current. In turn, the current of phase B behaves in an almost-regular way, whereas the current of phase A remains the same as before the fault. Regarding the three-phase voltage to ground, the amplitudes for the phases A and B present the expected increase, whereas the amplitude for the phase C drastically decreases as well as its waveform becomes quite distorted. In this case, the noticeable presence of both current and voltage harmonics suggests the occurrence of beats and ferroresonance, which may explain the mentioned non-regularity and distortion in the involved waveforms. If it is present, the ferroresonance may be caused by the interaction between the capacitances to ground of the cables of the feeders and the magnetizing reactance of the zig-zag transformer that may become magnetically saturated during the fault period.

In turn, because of the presence of harmonic components in the neutral current, the neutral overcurrent protection of the feeder F01 did not trip because it is blocked against inrush current through the detection of the presence of the second-order harmonics. Thus, since the fault phase C current may contain second-order harmonics, it disables the protection trip [18]. To confirm this proposition, Fig. 10 shows the spectrum of harmonic amplitudes of the current of phase C of the feeder F01 for the period of fault, which shows that the amount of the second-order harmonic, 31.1 % is significant enough to block the protection tripping.

FIGURE 10

Fig. 10. Case 2 - Spectrum of harmonic amplitudes of the current of phase C of the feeder F01.

This harmonic blocking is an option that is usually enabled on feeders´ protection for avoiding the undesired tripping due to the inrush current of each of the generating units when simultaneously switched on.

In addition, Fig. 11 shows the oscillography of the neutral current of the zig-zag transformer, which RMS value reached the value of about 536 A, that is greater than the value of 500 A, set as the limit to tripping.

FIGURE 11

Fig. 11. Case 2 - Oscillography of the neutral current of the zig-zag transformer.

Yet, from the oscillography of Fig. 11, it is possible to observe that the waveform of the neutral current of the zig-zag transformer does not present any significant harmonic distortion, which explains why it could protect the circuit during the fault without any interference of the harmonic block.

Moreover, in view of enabling deeper analyses for understanding the complexity of this case, the oscillography of the neutral current of the faulty feeder F01 is shown in Fig. 12. In comparison to the neutral current of the zig-zag transformer, it is significant the difference between the RMS values for the neutral current during the fault. Numerically, about 94 A for the feeder F01 and 536 A for the zig-zag transformer, which may seem somehow surprising.

FIGURE 12

Fig. 12. Case 2 – Oscillography of the neutral current of the feeder F01.

However, this difference occurs due to the phasor sum of the capacitive current of the underground cables and the inductive current caused by the leakage impedance of the zig-zag transformer, as it is illustrated in Fig. 3.b. Thus, since these current phasors are 180° out of phase, their sum is a phasor current with less amplitude than any of the individuals.

This same phenomenon does not occur when a resistor is used for grounding the available neutral of the collector transformer. In this case, as indicated in Fig. 3.a, because of the value of 90° of the phase difference between the resistive and the capacitive currents, their phasor sum always results in a phasor current with an amplitude higher than that at the fault point. To show this, computer modelling and simulations have been performed. Specifically, the electromagnetic transient software ATP [19] was used for modeling both the circuits shown in Figs. 3.a and 3.b, by assuming the value of the MV voltage as 34.5 kV, with 5% of pre-maneuver overvoltage and having one feeder only, but with a length of 70 km of underground cables for obtaining values of capacitive contribution equivalent to the real case of several feeders. Further details of this modelling are given in [15]. The obtained results for the behavior of the involved currents are shown in Fig 13.a for the case of the neutral of the collector transformer grounded by a resistor, in accordance with Fig. 3.a, and in Fig. 13.b for the case of the (virtual) neutral of the transformer grounded by a zig-zag transformer, in accordance with Fig. 3.b.

FIGURE 13.a

a. Grounded by a resistor.

FIGURE 13.b

b. Grounded by a zig-zag transformer.

Fig. 13. Waveforms obtained from ATP modeling and simulations for the fault current of the feeder F01, labeled as $3I_{co}$, and for the fault current of the neutral of the collector substation, labeled as $3I_o$ FTR - **a.** Grounding by a resistor; **b.** Grounded by a zig-zag transformer.

The simulated results numerically confirm the mentioned phasor differences in the sums of the involved currents. That is, based on Fig. 13.a, the RMS value of the neutral current in the collector substation, 658 A, is greater than that of the neutral current of the faulty feeder, 511 A, when the available neutral of the collector transformer is grounded by a resistor. In turn and based on Fig. 13.b, the RMS value of the neutral current in the collector substation, 94 A, is significantly less than that of the neutral current of the faulty feeder, 503 A, when the non-available neutral of the collector transformer is virtually grounded by a zig-zag transformer. In this case, the occurrence of parallel resonance is the reason for such a significant difference in the RMS values of the involved currents. This resonance causes the cancellation of the effects of the inductive leakage reactance of the zig-zag transformer neutral and the capacitive component of the current of the feeders' cables, which represents a significant challenge for properly setting the respective protection system relays.

C. Case 3 – The effect of the capacitance of the underground cables on the voltage after the fault clearance

In the third case, it is analyzed the influence of the capacitance of the underground cables on the behavior of the voltage waveform right after a single-phase fault is cleared. As in the previous case, this influence differs if the neutral of the collector transformer is grounded by a resistor or with a zig-zag transformer. With this aim, Fig. 14 shows the oscillography of the three-phase voltage to ground for the periods before, during, and right after the clearance of a single-phase to ground short-circuit in a feeder of a wind or solar power plant.

FIGURE 14.a

a. Grounded by a zig-zag transformer.

FIGURE 14.b

b. Grounded by a resistor.

Fig. 14. Oscillography of the three-phase voltage to ground for the periods before, during, and right after the clearance of a single-phase to ground short-circuit current of a feeder when the neutral of the transformer collector is grounded by – **14.a** zig-zag transformer; **14.b**. resistor.

The presented oscillography shows that when a zig-zag transformer is adopted for grounding the neutral of the collector transformer, its magnetizing reactance and the capacitance of the underground cables interact, causing the waveform of the transient recovering voltage to be significantly distorted right after the fault is cleared. This is evidence of ferroresonance. On the other hand, no distortion is present in the voltage for the same period when the adoption is of a grounding resistor.

Regarding the occurrence of the ferroresonant, it must be considered that the level of the corresponding transient voltage depends on the instant at which the fault current is interrupted, which has a random nature. Therefore, the level of overvoltage after the fault is cleared can be significantly more critical than that shown in Fig. 14.b.

Again, with the aim of deeply investigating this case, the same circuits deployed in the ATP study presented in Case 2 were used to simulate the interruption of the fault current, and the results are shown in Fig. 15.

FIGURE 15.a

a. Grounded by a zig-zag transformer.

FIGURE 15.b

b. Grounded by a resistor.

Fig. 15. Results of the ATP simulation of the three-phase voltage to the ground for the periods before, during, and right after the clearance of a single-phase to ground short-circuit current of a feeder when the neutral of the transformer collector is grounded by – **15.a** a zig-zag transformer; **15.b** a resistor.

Comparison between the results from oscillography, shown in Fig. 14, and ATP simulations, shown in Fig. 15. confirms how useful the adoption of ATP modeling and simulations for studies of protection of electric circuits can be because of the good representation of the practical cases that it allows. This is evident in the case of the neutral of the collector transformer grounded by a zig-zag transformer, for which the ATP simulations were performed until the highest value of transient overvoltage could be found and presented in Fig. 14.b, which indicates the possibility of transient ferroresonant interaction that may represent a threat for the whole MV circuit because of the overvoltage that may reach amplitude with values close to $\sqrt{3}$ times that of the fault period. Such a value of overvoltage can be harmful to installed equipment, especially to surge arresters.

In turn, no overvoltage or distortion occurs in the actual cases or in the simulation adopting the neutral grounded by a resistor. In both simulations performed, the three-phase voltage to ground behaves as it is predictable, that is, with an amplitude value of about $\sqrt{3}$ times the nominal value for the healthy phases and close to zero for the faulty one. Yet, the voltage amplitudes quickly return to their nominal value after the short-circuit is extinguished.

VI. CONCLUSION

As could be expected, when in the implantation of wind or solar power plants, the adoption of technical principles that are not familiar to the local engineering companies invariably involves urgent measures that range from study efforts, in order to understand those technical principles, to a transitional process of adoption of the locally usual technical principles. This is what is going on in areas within tropical latitudes of some countries, where the implantation of solar and wind power plants is booming. In tune with this important fact, this work has been developed to serve as an elementary basis or reference for helping those engineers who want to learn and preserve the technical principles adopted from abroad but are not familiar with them. Specifically, in regard to issues related to properly adjusting or setting the protective system devices to actuate when the occurrence of faults to ground. Namely, the combination of the adopted method for grounding the neutral of the collector transformer and the significant influence of the capacitance to ground of the underground cables, usually and widely deployed in the MV circuits or feeders. With this aim, this work has analyzed three typical cases of single-phase short circuits to ground that synthesize most of the concerns claimed by engineers involved in implantation and operation of that sort of wind and/or solar power plants. Among the conclusions obtained in this work, the main ones are that for grounding the neutral of the transformer collector, there are two predominant options that are by using a resistor or a zigzag transformer, since the option for the solidly grounded is technically discarded. Based on the presented cases, the resistor is the preferable option, although it is far from being perfect. Nonetheless, its adoption depends on the availability of the neutral point of the collector transformer. In cases when this neutral point is not available, the zig-zag transformer is the only option, although it represents significantly more concerns with relays adjustment and coordination as well as with transient overvoltage. Thus, because of the unavoidable presence of underground cables, which lends a capacitive component to the currents of faults to ground, the adjustment of the protective systems is the key concern, no matter what the

choice is for the method for grounding the neutral point. With this aim, the aid provided by computer programs with transient analyses plays a very important role in studies of specific conditions, together with data from oscillography of the digital relays, as performed in this work.

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Figures

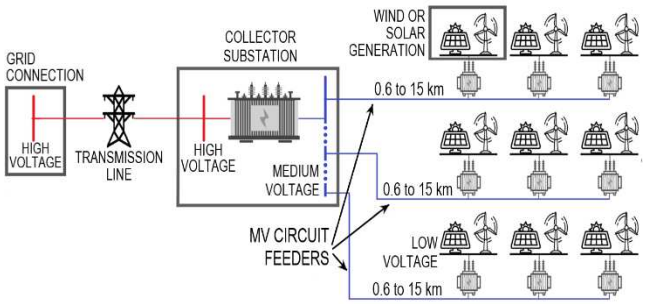


Fig. 1. Typical configuration of the electric circuit of a wind or solar power plant.

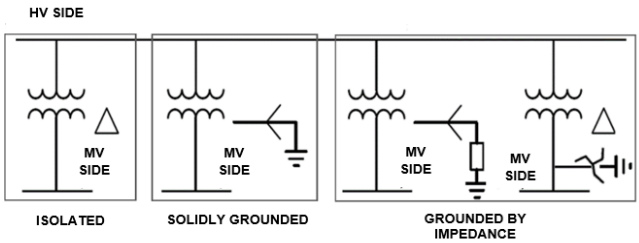


Fig. 2. Diagram of the methods of transformer neutral grounding.

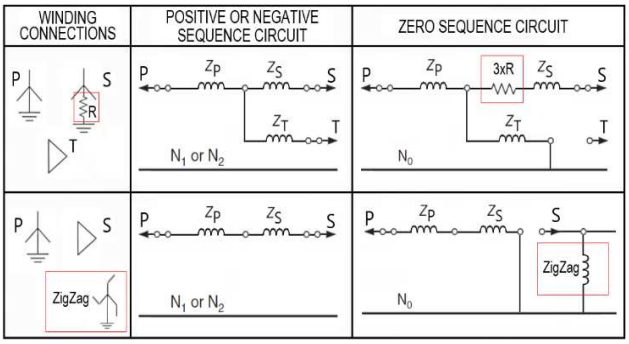


Fig. 3. Behavior of the single-phase to ground short-circuit current for the method of neutral grounding by impedance. With a resistor - upper; With a zig-zag transformer - lower.

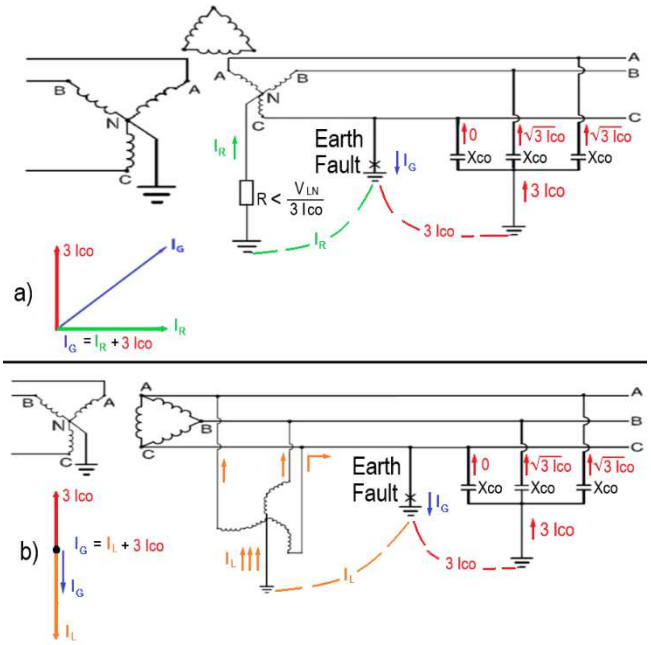


Fig. 4. Circuits of the diagram of sequences for the two types of the method of neutral grounding by impedance. Upper - with a resistor and a tertiary winding. Lower - with a zig-zag transformer.

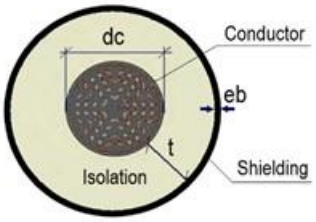


Fig. 5. Cross-section of a typical underground cable.

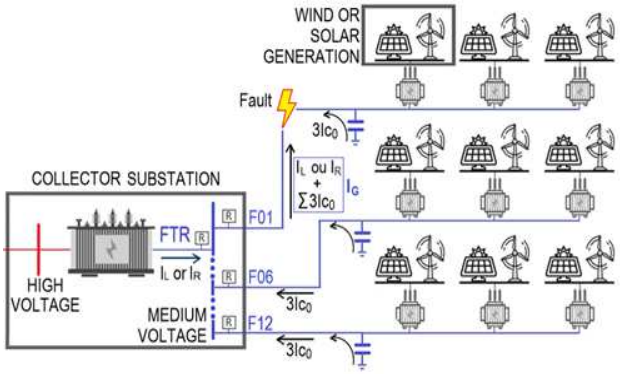


Fig. 6. Single-phase diagram of a wind/solar power plant under the occurrence of a single-phase to ground fault.

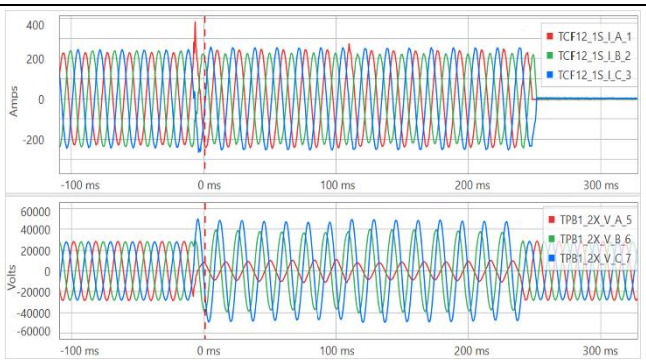


Fig. 7. Case 1 – Oscillography of the three-phase voltage and current of feeder F12 during the fault.

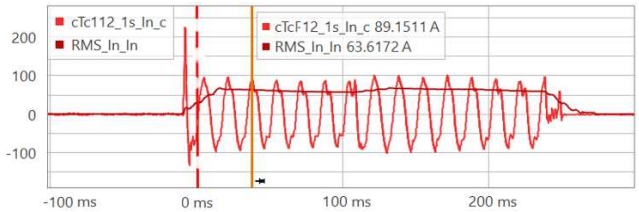


Fig. 8. Case 1 – Oscillography of the neutral current of the feeder F12.

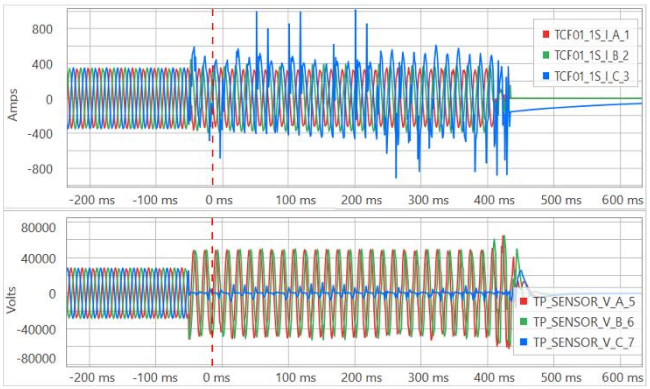


Fig. 9. Case 2 – Oscillography of voltage and current of the feeder F01 during the fault

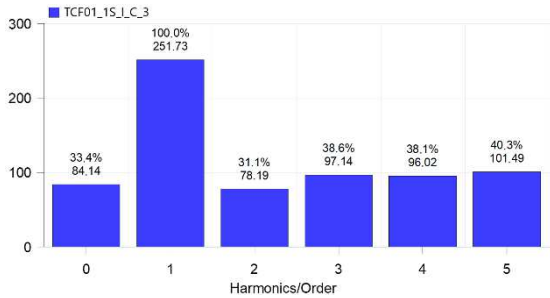


Fig. 10. Case 2 - Spectrum of harmonic amplitudes of the current of phase C of the feeder F01.

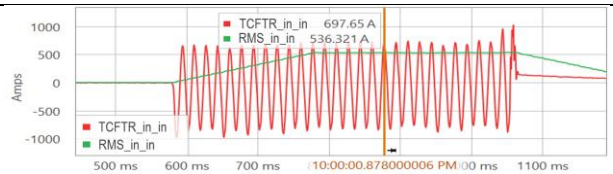


Fig. 11. Case 2 - Oscillography of the neutral current of the zig-zag transformer.

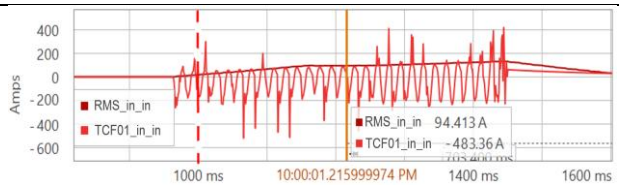
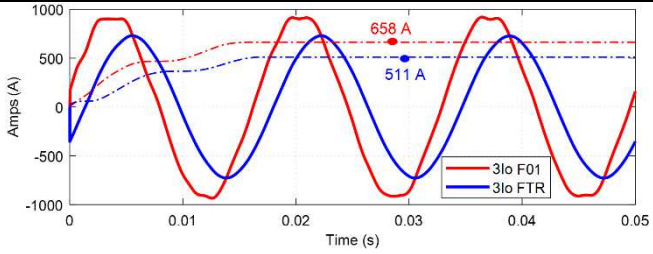
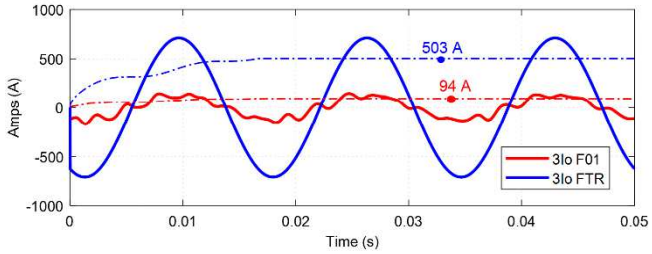


Fig. 12. Case 2 – Oscillography of the neutral current of the feeder F01.

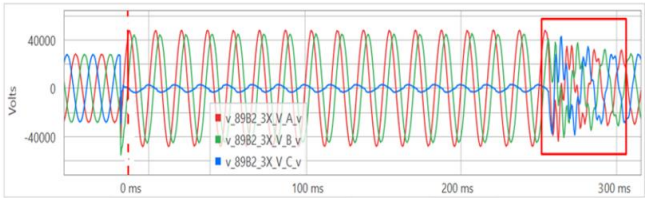


a. Grounded by a resistor.

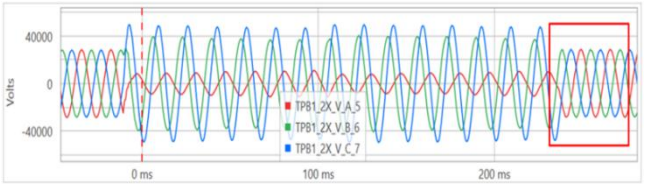


b. Grounded by a zig-zag transformer.

Fig. 13. Waveforms obtained from ATP modeling and simulations for the fault current of the feeder F01, labeled as 3Ico, and for the fault current of the neutral of the collector substation, labeled as 3Io FTR - a. Grounding by a resistor; b. Grounded by a zig-zag transformer.

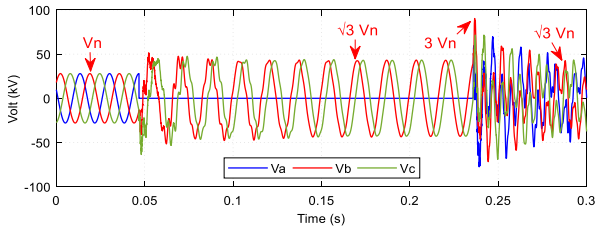


a. Grounded by a zig-zag transformer

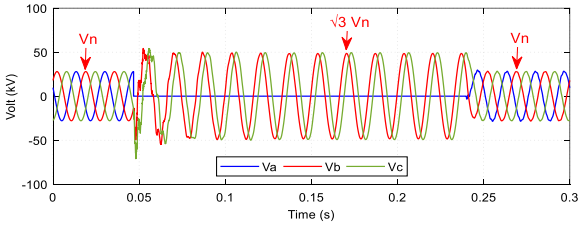


b. Grounded by a resistor.

Fig. 14. Oscillography of the three-phase voltage to ground for the periods before, during, and right after the clearance of a single-phase to ground short-circuit current of a feeder when the neutral of the transformer collector is grounded by – 14.a zig-zag transformer; 14.b resistor.



a. Grounded by a zig-zag transformer.



b. Grounded by a resistor.

Fig. 15. Results of the ATP simulation of the three-phase voltage to the ground for the periods before, during, and right after the clearance of a single-phase to ground short-circuit current of a feeder when the neutral of the transformer collector is grounded by – **15.a** a zig-zag transformer; **15.b** a resistor.

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