A proposal of Hybrid Resistive-Inductive Grounding to limit both Transient Overvoltages and Ground-Fault Currents in High-Voltage Electrical System

R. S. Ferreira, H. H. Favoreto

***Abstract*-- High-voltage industrial power systems are typically grounded using high resistance to limit ground-fault current and control overvoltages during intermittent ground faults. This resistance is designed so that the resistive current exceeds the system's total capacitive current. In large systems with numerous rotating machines and surge capacitors, the high capacitive current significantly increases the total ground-fault current, potentially damaging the stator core of generators and motors in the event of an internal ground fault. A grounding transformer with a grounding resistor connected at the neutral of generators can reduce the capacitive current and total fault current, but the voltage must be maintained at the resistor for proper protection, thus limiting the total ground fault reduction.**

This paper proposes a hybrid resistive-inductive grounding solution to reduce ground-fault current while maintaining overvoltage at safe levels. Initially, both purely inductive and hybrid grounding solutions are studied in detail. Criteria for specifying a hybrid grounding are proposed and applied to a real industrial power system, and the solution is verified under expected operating conditions.

***Keywords*: hybrid grounding, intermittent ground faults, industrial power system, rotating machines.**

I. INTRODUCTION

High-voltage industrial power systems are typically grounded using a high resistance, which is used to limit ground-fault current and control the overvoltages in the event of intermittent ground faults [1]-[6]. This resistance is calculated so that the resistive current is greater than the capacitive current. In large industrial power systems with numerous rotating machines equipped with surge capacitors and insulated cables, the capacitive current is high. Consequently, the resistive current and the total ground-fault current increase, leading to damages in the stator core of the rotating machines in the event of a ground fault within the machine [7]-[9]. When a ground fault occurs internally to a generator the current flows from the stator conductors to the core. In this case if the current is great enough it can damage the core in a such a way that it is not possible to repair the core sheets. Fig. 1 shows a typical stator core damage curve where the repairable and non-repairable areas are defined. Considering that the primary electrical protections actuate in approximately 100 ms, according to Fig. 1 the ground fault current shall be limited to 100 A

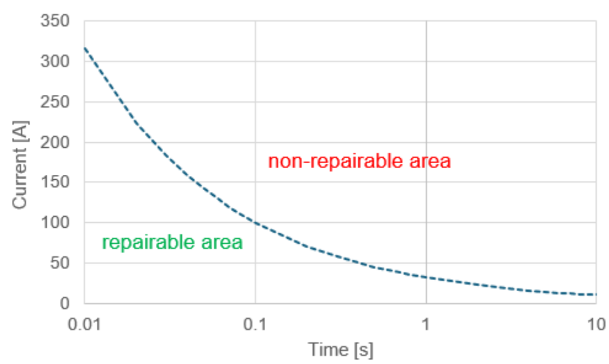

Fig. 1. Typical limit of repairable core damage for stator winding ground fault to core.

To address this, a grounding transformer with a grounding resistor can be used to eliminate part of the capacitive current, thereby reducing the total fault current. However, the total ground-fault current cannot be significantly reduced, as a significant percentage of the voltage must be maintained at the resistor to ensure proper protection actuation.

To reduce the total ground-fault current, a well-known solution is to use resonant grounding, where the system is grounded by a reactor tuned to the system's capacitive current [10]. The major challenge of this solution in industrial power systems is that the capacitive current varies significantly according to the operating conditions, such as the plant configuration and the loads in operation. Therefore, application of resonant grounding shall be analyzed carefully in industrial power systems.

This paper aims to propose a hybrid resistive-inductive solution that can reduce the total ground-fault current while maintaining overvoltages at safe levels. For this purpose, both a purely inductive solution and a hybrid solution for grounding the system are studied in detail. Subsequently, the criteria for specifying a hybrid grounding are proposed and applied to a real industrial power system. The proposed solution is verified under the expected operating conditions of the system.

II. INDUCTIVE GROUNDING

In order to reduce the total ground fault current, the first possibility which arrives is to ground the generators by

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reactors instead of resistors. In this case the reactor can be designed so that the inductive current cancel part or the total capacitive current, hence reducing the total ground fault current. In the case the inductive current is equal to the capacitive current and there will be no ground fault current, and this is known as a resonant or neutralizer grounding type [10].

Some simulations are performed to verify the overvoltages in the system when an inductive grounding is used to better understand the effects involved. Based on [10][12], the simplified system presented in Fig. 2 is used to simulate transient overvoltages following the occurrence and clearing of a single-phase fault to ground in ATPDraw [14].

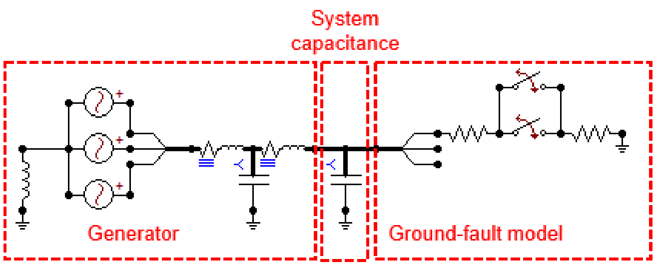

Fig. 2. Simplified system used to study transient overvoltage in a reactance grounded generator.

A. Variation of Reactance

The system studied consist of a 13.8 kV generator modelled by the subtransient reactance and the winding capacitance to ground, in a "T" model as indicated in [10][12]. The fault is modelled by the two time-controlled switches indicated in Fig. 2, which are closed and opened to simulate the occurrence, clearing and ignition of the fault. Additionally, in the model it is also considered one capacitance to model the system.

Firstly, simulations have been performed by varying the reactance at the neutral point of the generator and the results summarizes the overvoltage as a function of the X_0/X_1 ratio, where X_1 is the sub-transient reactance of the generator and X_0 is the generator zero-sequence reactance (considered equal do X_1) plus $3X_N$, where X_N is the neutral reactance.

The fault was applied at the instant the voltage at phase A to ground was equal to its crest value and removed at the first current zero. A second situation was studied by reapplying the fault at crest recovery voltage across the fault and then removed at the first current zero following the restrike or fault reapplication. For all the cases, the inductive current (neutral current) is much higher than the total capacitive current of the system.

Fig. 3 shows the results without restrike, that is, the fault is applied and removed and Fig. 4 shows the results with one restrike (1 pu voltage is related to the peak value of the phase to ground voltage). According to the figures, the results are similar to those presented in [10][12], which indicates a correct modelling for the events. Additionally, the results allow us to conclude that X_0/X_1 ratio shall remain up to 4 to keep the overvoltages below 2.6 pu, which corresponds that the neutral reactance (X_N) shall be less than or equal to the subtransient reactance of the generator ($X_N \leq X_1$).

Additionally, the waveforms in the time domain are also presented. Fig. 5 and Fig. 6 show the results for phase to ground voltages and neutral to ground voltage without restriking and X_0/X_1 ratio equal to 3, where is possible to see that the voltages remain below 2.6 pu, however due to very low resistance considered the overvoltage is not damped.

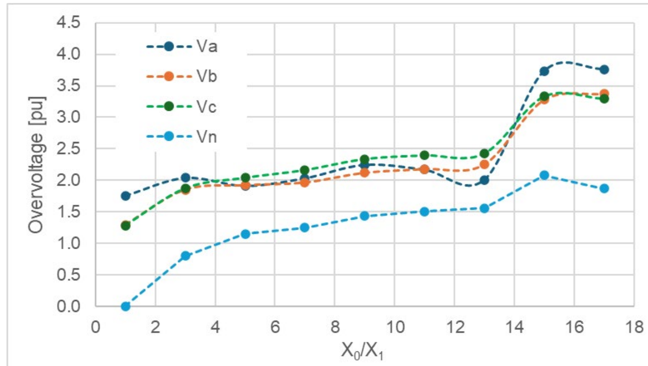

Fig. 3. Overvoltage as a function of X_0/X_1 with no restrike.

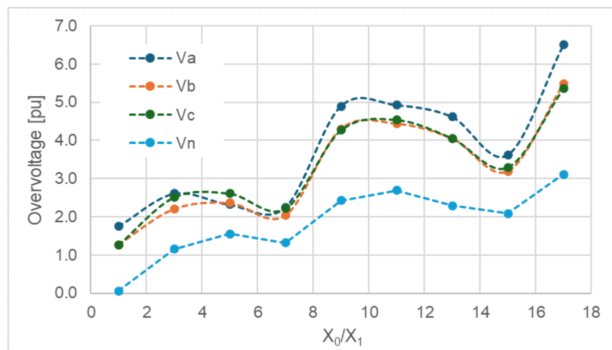

Fig. 4. Overvoltage as a function of X_0/X_1 with one restrike.

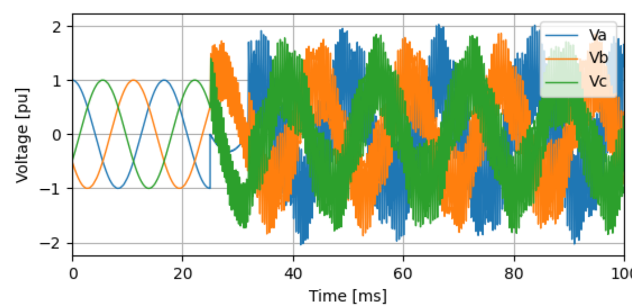

Fig. 5. Phase to ground voltages without restriking for $X_0/X_1 = 3$.

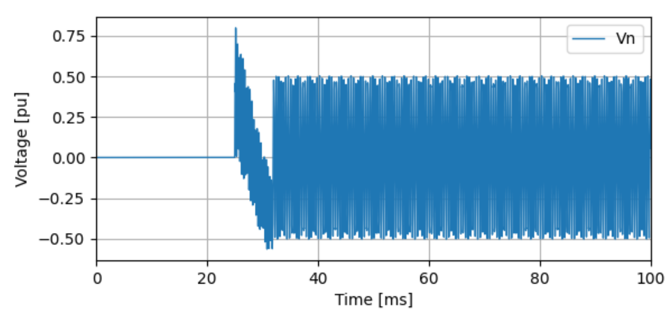

Fig. 6. Neutral to ground voltages without restriking for $X_0/X_1 = 3$.

Fig. 7 and Fig. 8 present the waveforms when one restriking is considered for a X_0/X_1 ratio equal to 13. According to the results, the phase overvoltages are well superior of 2.6 pu, which emphasizes the impossibility to operate with a neutral grounded by a high reactance.

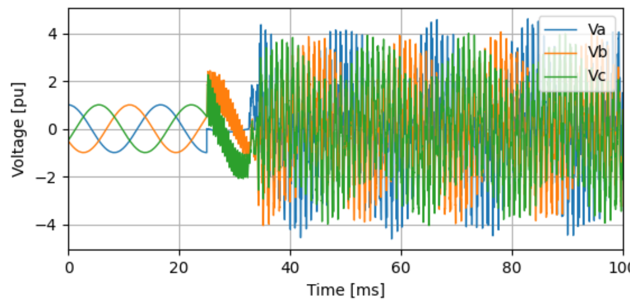

Fig. 7. Phase to ground voltages with one restriking for $X_0/X_1 = 13$.

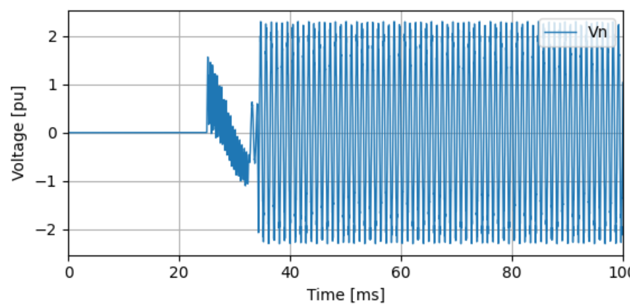

Fig. 8. Neutral to ground voltage with one restriking for $X_0/X_1 = 13$.

The previous pictures have presented results for both, phase to ground and neutral to ground voltages. The neutral to ground voltage is important to verify the stresses at the neutral devices and the phase to ground voltages are used as the limit to design the grounding system. Normally, the systems are designed so that the phase to ground voltage remains below 2.6 pu in case of intermittent ground faults. This is considered, because the rotating machines are tested with a voltage withstand test of 3.58 pu at factory according to [13], which also states that if necessary to repeat the voltage withstand test it shall be performed with 80% of the full voltage, which gives 2.87 pu. Therefore, the value of 2.6 pu is considered to have a safe margin for the standard values. Fig. 9 summarizes these values of voltage.

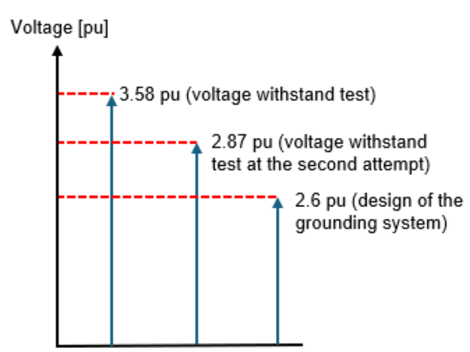

Fig. 9. Limit of overvoltage for designing a neutral grounding system.

B. Variation of Capacitance

A second set of simulations is performed considering the variation of the system capacitance. For these simulations only the case with restriking has been considered, since it refers to the worst scenario. The main objective is to understand the influence of the capacitance on the overvoltage considering that a resonant grounded is used in practice and when the reactor is not tuned with the system capacitance.

During the investigation it was verified that the ratio between the total capacitive current (charging current) and the neutral inductive current has influence on the results. Fig. 10 presents the overvoltages obtained as a function of the ratio $3I_C/I_L$.

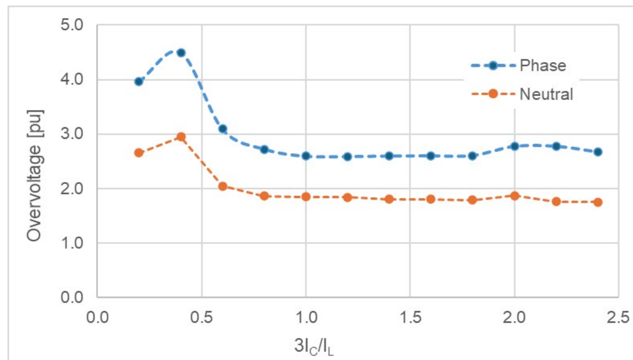

Fig. 10. Overvoltage as a function of $3I_C/I_L$ with one restrike for an inductive grounding.

According to the results it is possible to see that when the system capacitance current is tuned to the neutral current, that is, the total capacitive current is equal to the inductive current (representing the resonant grounding system) the overvoltages are limited to 2.6 pu. For ratios below 0.6 the overvoltages are above 3 pu, which is explained by the fact that in this case the fault current is inductive, hence high overvoltages are expected when this inductive current is switched. For ratios above 2, it was also observed overvoltages above 2.8 pu, which are explained by the fact that the total capacitive current in this region is more than twice the neutral current.

Therefore, if a pure reactor is used, the ground-fault current cannot be limited to very low values in order to prevent generator's stator core damage.

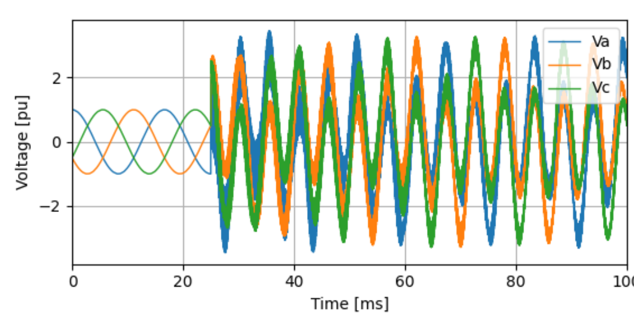

Fig. 11. Phase to ground voltages with one restriking for $3I_C/I_L = 0.1$.

Fig. 11, Fig. 12 and Fig. 13 present the voltage waveforms for different ratios of the total capacitance current and the inductive neutral current to emphasizes the amplitudes presented in Fig. 10.

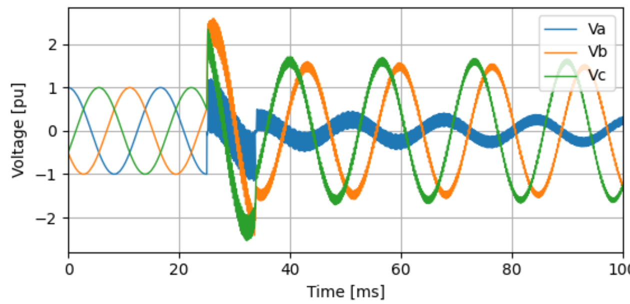

Fig. 12. Phase to ground voltages with one restriking for $3I_C/I_L = 1$.

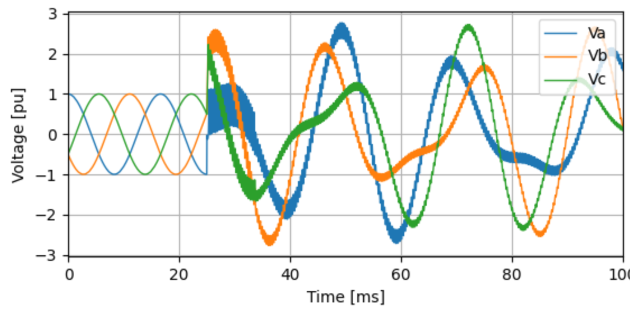

Fig. 13. Phase to ground voltages with one restriking for $3I_C/I_L = 2$.

III. Hybrid Grounding

The previous results have showed that it is possible to operate with a resonant grounding system. In fact, it seems to have a range next to the tuned region which is possible to have a viable inductive neutral grounding, however this region seems to be very limited. Therefore, in this section it is evaluated the results when the neutral is hybrid that is, the grounding is achieved by an inductive and a resistive current. The same system presented in Fig. 2 is used in this section and the simulations are performed considering a neutral current equal to 25 A with the resistive current equal to the inductive current. The total capacitive current of the system is varied from 2.5 A to 60 A.

Fig. 14 presents the overvoltages as a function of the ratio between the total capacitive current and the inductive current. As observes, only for rations below 0.5 the overvoltages are above 2.6 pu, which is similar to the previous conclusion with the pure inductive grounding.

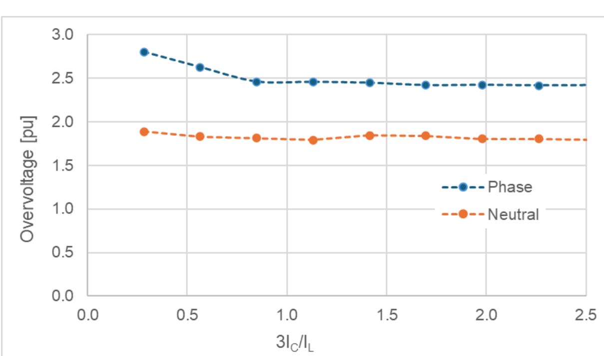

Fig. 14. Overvoltage as a function of $3I_C/I_L$ with one restrike for a hybrid grounding.

Fig. 15, Fig. 16 and Fig. 17 present the voltage waveforms for different ratios of the total capacitance current and the inductive neutral current.

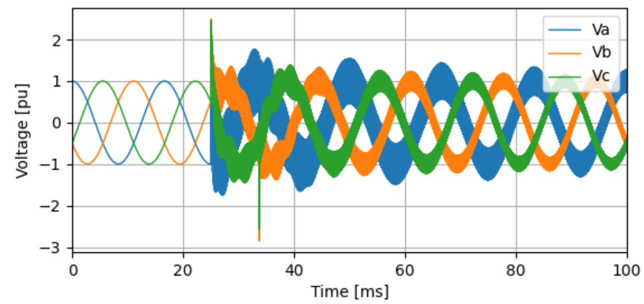

Fig. 15. Phase to ground voltages with one restriking for $3I_C/I_L = 0.1$ for a hybrid grounding.

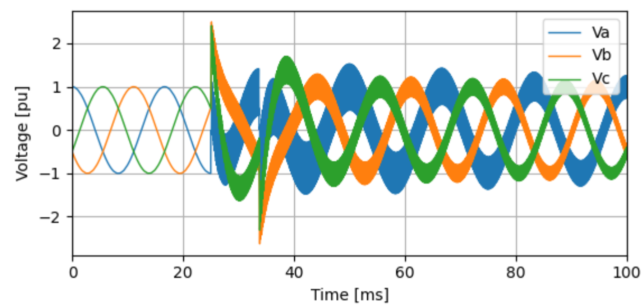

Fig. 16. Phase to ground voltages with one restriking for $3I_C/I_L = 0.6$ for a hybrid grounding.

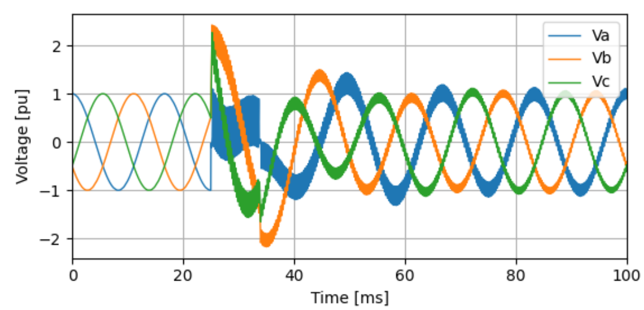

Fig. 17. Phase to ground voltages with one restriking for $3I_C/I_L = 2$ for a hybrid grounding.

Therefore, according to the results when the resistor is added to the neutral the overvoltages are much more damped and the ratio $3I_C/I_L$ has influence on the overvoltages. As can be seen in Fig. 14, for $3I_C/I_L > 0.6$ the overvoltages are limited to 2.6 pu. Therefore, the design criteria chosen for the hybrid system is to consider:

a) $3I_C/I_L \geq 0.6$
b) $I_N/3I_C \geq 0.7$, based on results presented in [1], where I_N is the total neutral current.

The abovementioned criteria shall be verified for all possible operational conditions in the electrical system in order to be sure there is no case that they are not met.

IV. Study Case

In order to apply the design criteria previously defined, a hybrid grounding system is proposed to an industrial power system. As can be seen in Fig. 18, the electrical system is composed of four main turbogenerators directly connected in the main switchgear, in 13.8 kV, and normally all of them are grounded by a resistor connected to the secondary of a grounding transformer. In the main switchgear there are several loads, which are motors and power transformers. Motors are star isolated connected and power transformers have always the primary winding connected in delta, which means that the grounding of the 13.8 kV system is segregated from the other lower-voltage systems, hence they can be disregarded by the analysis.

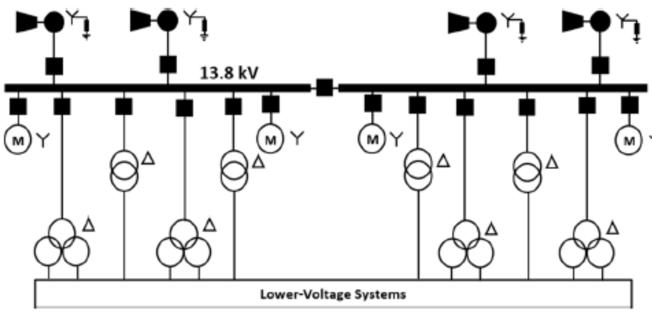

Fig. 18. Electrical system under analysis.

The system can operate with all possibilities of number of generators and loads, hence with different capacitance for each number of generators. To allow a proper evaluation, the minimum and maximum capacitances for each scenario has been enumerated as indicated in TABLE I.

According to the values, the maximum capacitance is obtained in the case with 4 generators and the total charging current ($3I_C$) is 121.6, which is already greater than 100 A, hence with the traditional methods of neutral grounding (resistor or resistor at the secondary of a grounding transformer) it is not possible to keep the total ground fault less than 100 A to avoid damage in the generators stator core (see Fig. 1). In addition, regarding all scenarios it is clear that the capacitance varies to much which difficult to achieve both criteria defined in the last section.

TABLE I
MINIMUM AND MAXIMUM CAPACITANCE PER OPERATING SCENARIO.

Number of Generators	Minimum Capacitance		Maximum Capacitance	
	[µF]	$3I_C$ [A]	[µF]	$3I_C$ [A]
1	0.7	6.4	4.25	38.3
2	5.0	44.7	8.5	76.6
3	9.2	83.0	12	108.1
4	12.7	114.6	13.5	121.6

The solution considered for this system was to use the generators grounded by grounding transformers with resistors at their secondaries and reactors plus zigzag transformers connected directly to the main switchgear to reduce the total ground fault current. This solution was used since the way the generators are typically grounded is not changed and to avoid possible overvoltage at the generators in case of intermittent ground faults when they operate with no-load disconnected to the main switchgear.

The premises used to the obtain the inductive and resistive currents were:

a) the zigzag transformer will only operate with high capacitance content on the system, that is, with 3 and 4 generators (for a lower number of generators, it is not required to include an inductive grounding, since the total ground-fault current can be limited to 100 A);

b) the inductive current of the zigzag transformer (I_{LZ}): was adjusted to eliminate the total capacitance at the scenario with the maximum charging current;

c) the resistive current of the grounding transformer and resistor (I_{RG}) was adjusted to the maximum possible current from the stator core damage curves (100 A, in this case) divided by the number of generators;

c) the inductive current of grounding transformer and resistor (I_{LG}) was adjusted to 1.5 times the minimum capacitance (1 generator) in order to comply with the overvoltage criteria ($3I_C/I_L \geq 0.6$ and $I_N/3I_C \geq 0.7$);

d) the inductive current of the zigzag transformer (I_{LZ}) was adjusted to keep the total ground fault current less than 100 A and to comply with the overvoltage criteria ($3I_C/I_L \geq 0.6$ and $I_N/3I_C \geq 0.7$).

Considering the abovementioned premises the following system was designed according to

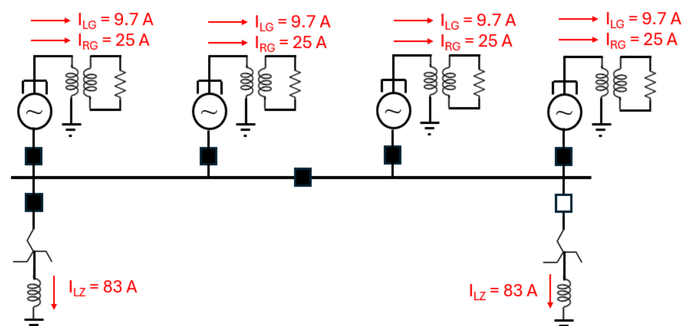

Fig. 19. Proposed hybrid grounding system.

TABLE II presents the calculated current and TABLE III shows the verification of the design criteria for each operating scenario. As can be seen the total ground current was limited to 100 A, even with a total capacitive current ($3I_C$) of 121.6 A. If a pure resistor had been used the total ground fault current would be 172 A ($121.6 \times \sqrt{2}$), which shows the importance of the hybrid system in this case with high charging current. In addition, the ratios $I_N/3I_C$ and $3I_C/I_L$ are always above the criteria for all operating scenarios.

Fig. 20 shows the system currents and Fig. 21 presents the total ground-fault current and the voltage at the neutral for the scenario with the highest capacitance. From the pictures it is possible to see that the inductive current of the generator neutral and from the zigzag transformer cancel the total capacitive current in such a way that the total ground fault is almost in phase with the neutral voltage, that is, the equivalent fault current is nearly resistive.

TABLE II
CURRENTS CONSIDERED PER OPERATING SCENARIO.

Number of Generators	Currents			
	I_{LZ} [A]	I_{LG} [A]	I_{RG} [A]	I_N [A]
1	0.0	9.7	25.0	26.8
2	0.0	19.3	50.0	53.6
3	83.0	29.0	75.0	134.8
4	83.0	38.7	100.0	157.5

TABLE III
VERIFICATION OF THE CRITERIA FOR EACH OPERATING SCENARIO.

Number of Generators	Minimum Capacitance			Maximum Capacitance		
	$I_N/3I_C$	$3I_C/I_L$	I_F [A]	$I_N/3I_C$	$3I_C/I_L$	I_F [A]
1	0.70	3.96	38	4.2	0.67	25
2	0.70	3.96	76	1.2	2.31	56
3	1.25	0.97	75	1.6	0.74	80
4	1.29	1.03	100	1.4	0.94	100

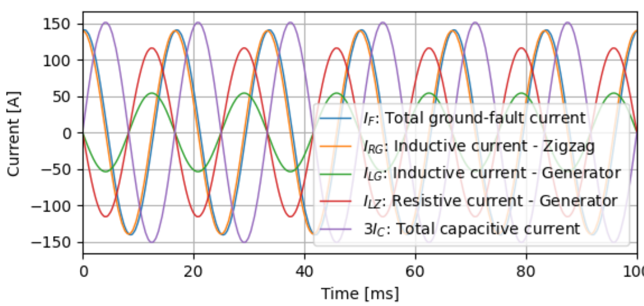

Fig. 20. System currents for 4 generators and maximum capacitance operating condition.

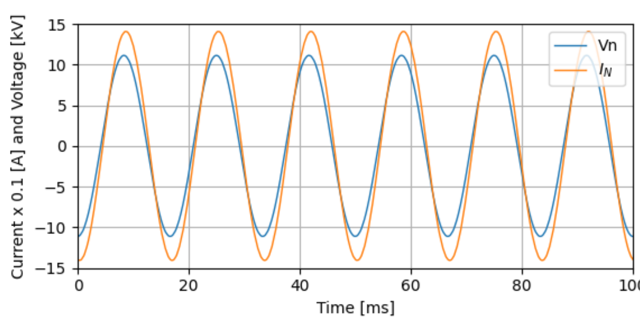

Fig. 21. Total ground-fault current and voltage at neutral for 4 generators and maximum capacitance operating condition.

To verify the effectiveness of the proposed criteria to control the overvoltages in case of intermittent ground faults, simulations of all operating cases have been conducted which results are summarized in TABLE IV.

According to the values presented in TABLE IV, the overvoltages are always limited to 2.6 pu as expected. In fact, the worst result was observed for the case with minimum capacitance for 1 generator, which is the case with the lowest $I_N/3I_C$ ratio.

TABLE IV
OVERVOLTAGE SIMULATED FOR EACH OPERATING SCENARIO.

Number of Generators	Minimum Capacitance		Maximum Capacitance	
	[kV]	[pu]	[kV]	[pu]
1	29.4	2.6	27.2	2.4
2	26.7	2.4	26.7	2.4
3	26.3	2.3	26.2	2.3
4	26.2	2.3	26.1	2.3

The waveforms obtained for some of the operating scenarios are presented from Fig. 22 to Fig. 25 and they are all valid for one restrike. The waveforms show that the resistive current damps the overvoltage in each new reignition and the frequency of the overvoltage is affected by the equivalent capacitance and inductance for each scenario.

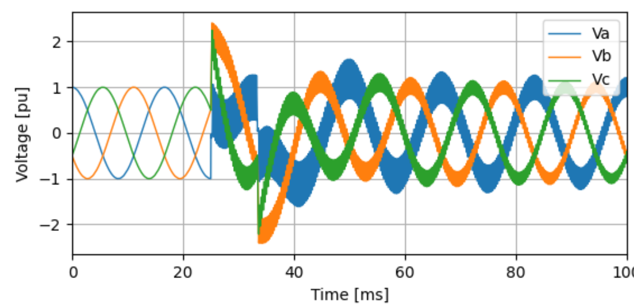

Fig. 22. Overvoltage for 1 generator and maximum capacitance operating condition.

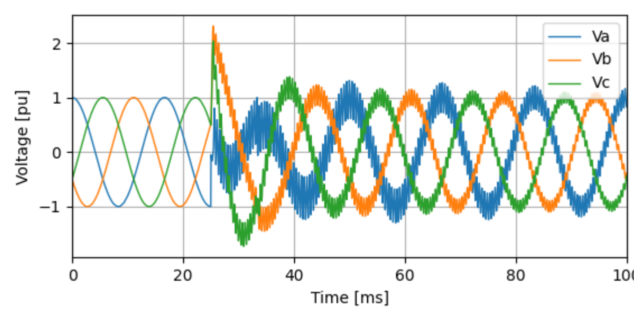

Fig. 23. Overvoltage for 4 generators and maximum capacitance operating condition.

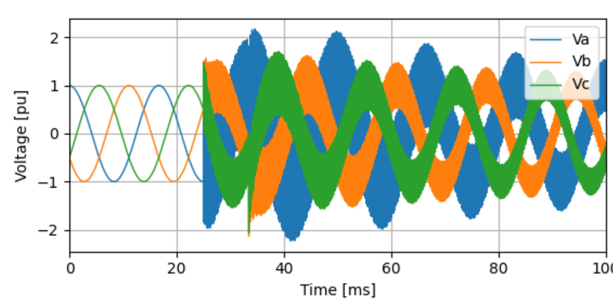

Fig. 24. Overvoltage for 1 generator and minimum capacitance operating condition.

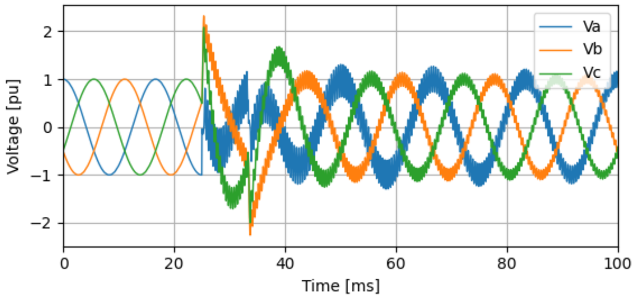

Fig. 25. Overvoltage for 4 generators and minimum capacitance operating condition.

V. Conclusions

In high-voltage industrial power systems with numerous electrical machines, the charging current becomes significantly high due to the large number of surge capacitors and insulated cables. Consequently, the total ground-fault current in a resistance-grounded system increases substantially, posing a risk of stator core damage in the event of an internal ground fault. While resonant grounding systems are typically employed to address this issue, they may not be suitable for systems with variable capacitance due to operational scenarios.

This paper proposes a hybrid resistive-inductive grounding solution to reduce the total ground-fault current while maintaining the overvoltages at safe levels. Both purely inductive and hybrid grounding solutions were thoroughly analyzed using a transient model. A design criterion was established for the hybrid solution, which includes maintaining the neutral current above 70% of the total capacitive current and ensuring the capacitive current is above 60% of the inductive neutral current for all possible operational conditions. The hybrid solution was implemented in a real industrial power system, and the proposed criteria were validated through simulations of intermittent ground faults.

In conclusion, the hybrid solution demonstrated an effective balance in reducing total ground fault current and limiting overvoltages within practical limits. Additionally, the proposed criteria proved to be effective when applicable to a real industrial power system application.

It is important to highlight that the proposed solution is more expensive and complex than conventional resonant grounding. However, it is applicable in scenarios where the capacitance varies over time due to operational conditions, and limiting the total ground fault is crucial. Resonant grounding may not be used in these cases, as it could lead to high overvoltages due to inductive ground fault currents in situations with low capacitive currents. The proposed solution has limitations when the difference between the minimum and maximum capacitance is very high, making it challenging to reduce the total ground fault current to very low values while keeping the overvoltage at safe levels.

VI. References

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