USE OF HYBRID RESISTIVE-INDUCTIVE GROUNDING ON 2 INTERCONNECTED PRODUCTION UNITS

Paper No. PCIC Europe EUR25_31

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Abstract - Medium voltage electrical systems of offshore production platforms are typically grounded using high resistance to limit ground-fault currents and control transient overvoltages. However, these electrical systems are becoming larger due to the trend of electrification as a solution to decarbonize operations and increase production efficiency. In the case of two offshore production platforms connected at 13.8 kV by submarine cables, ground-fault currents can be extremely high due to the cumulative charging capacitance of the electrical equipment. Such currents have the potential to damage the stator cores of generators and motors in the event of an internal ground fault.
To address this issue, this paper demonstrates how a hybrid resistive-inductive grounding solution can be designed to reduce ground-fault currents while keeping overvoltages within safe limits in the new electrical system formed by the interconnection of the two offshore production platforms.

Index Terms — System grounding, ground-fault current, transient overvoltages, electrification, production unit interconnection

I. INTRODUCTION

Oil and gas producers are investing more and more in electrification in the last years with the objective to increase energy efficiency, production efficiency, equipment's reliability and to decarbonize their operations. In addition, oil and gas companies are building production units with increasingly higher power demands, since their production capacities are increasing, and electrical motors are the main drivers of main mechanical equipment such as compressors and pumps.

In brownfield production units, to increase the oil and gas production, sometimes it's necessary to install additional electrical loads such as new electrical motors to drive subsea pumps and hence it's necessary to supply more power to the system [1]. If the production unit has a limited number of generators that have not been designed to supply additional loads with spare capacity, it's necessary to increase the generation capacity. Increasing the generation capacity, it's possible to avoid production losses due to unexpected generator's trip or planned maintenance [1].

In the previous case, if there is a production unit with spare generation capacity close to the one that needs additional power supply, one of the possible solutions is to import power from the unit with spare generation capacity to maintain generation redundancy in the unit that lacks a standby generator.

With the solution of importing power from a different production unit, a technical feasibility study was performed to assess the possibility to interconnect two brownfield FPSOs in deep waters by subsea power cables [2].

One of the interconnection topologies analyzed was the interconnection of the units using 3 submarine cables at a voltage level of 13.8 kV, that is, without the use of step-up transformers. This interconnection topology is shown in Fig. 1.

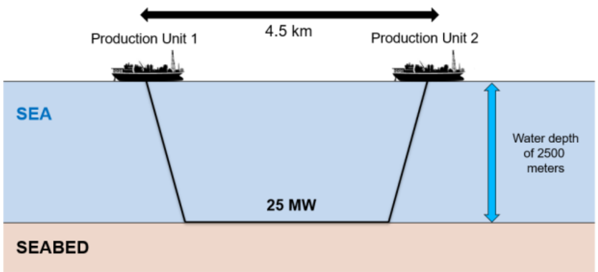

Fig. 1 Electrical interconnection topology at 13.8 kV

Regarding the topology in Fig. 1, one of the concerns raised by the study group was the likely excessive value of ground-fault current, which would make this option unfeasible. However, this solution could be advantageous due to the lower impact of modifications on the topsides of the FPSOs.

On the other hand, another possible topology, which consists of using 25 MW (power factor of 0.83) power transformers for transmission at 33 kV or 66 kV, would isolate the electrical systems and would not cause an increase in the ground-fault short-circuit level of the electrical systems. However, this second option would have disadvantages associated with the greater impact of modifications on the topsides of the FPSOs due to the need for installing large transformers [2].

Thus, with the aim of verifying whether the topology in Fig. 1 would have issues in ground-fault short-circuit events, this paper presents the study with the objective of answering the following question: Is it possible to transmit 25 MW (30 MVA) at 13.8 kV using 3 three-core submarine cables of 12 km between production unit 1 and production unit 2?

II. METHODOLOGY

The events of ground faults were simulated through software widely used in the electrical engineering area to evaluate the system's performance. The event was studied with a tool of mid-term and long-term transients. As a complementary tool, excel spreadsheets were also used for this preliminary study.

Regarding the assessment of maximum transient overvoltages, the simulations were performed by ATP (Alternative Transient Program).

III. MODELING ASSUMPTIONS FOR MID-TERM AND LONG-TERM TRANSIENTS

In the following subsections, the assumptions used for modeling each electrical equipment employed in the simulations are presented.

A. Generators

The model available in the files sent by the company contracted to carry out the electrical studies of FPSOs 1 and 2 during the design phase was used. Some of these parameters used are: resistance and leakage reactance of the stator, d and q subtransient reactances, d and q transient reactances, d and q synchronous reactances, and d and q mutual reactances of the rotor [2].

B. Grounding impedance of the generators

Each generator has a single-phase grounding transformer, with the primary terminals connected between the neutral and ground, and the secondary terminals connected to a resistor. Fig. 2 illustrates the grounding of the generators [2].

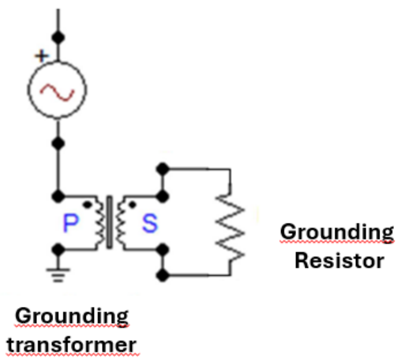

Fig. 2 Generator grounding

The resistor connected to the secondary of the transformer has different taps for selecting its resistance. The currently available resistances are shown in Table I.

TABLE I
GROUNDING RESISTOR DATA

Primary	Secondary	
TAP (A)	Resistance (Ω)	TAP (A)
15	0.0805	862.5
20	0.0384	1150.0
25	0.0122	1437.5

The grounding transformer data is shown in Table II.

TABLE II
GROUNDING TRANSFORMER DATA

Rated Voltage	35 kVA
Nominal voltage	13800/240 V
Short-circuit impedance	5.2 %
X/R	2.215

With the resistor tap information adjusted to 25 A in the units, the equivalent impedance between the neutral and ground of each generator is 156.76 + 257.88j Ohms. Fig. 3 shows the equivalent impedance.

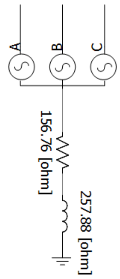

Fig. 3 Equivalent impedance between generator neutral and ground

C. Motors, transformers, cables, surge capacitors

The zero, positive, and negative sequence impedances of these equipment were considered negligible due to the high value of the grounding impedance of the generators.

These equipment were modeled through their equivalent capacitances of each phase to ground [2].

D. Total equivalent capacitances of the FPSOs 1 and 2 units

The capacitances of the motors, transformers, generators, cables, and surge capacitors were summed for each operating scenario and represented by a total equivalent capacitance per phase to ground connected to the 13.8 kV bus, for both units.

The equivalent capacitances per phase, which depend on the operating scenario of each unit, are shown in Table III and Table IV for FPSO 1 and FPSO 2, respectively [2].

TABLE III
EQUIVALENT CAPACITANCES OF FPSO 1

Scenario	Number of generators in operation	Capacitance (µF)
4R	1	2.17
1R	2	5.23
2R	3	7.63
3R	4	8.30

TABLE IV
EQUIVALENT CAPACITANCES OF FPSO 2

Scenario	Number of generators in operation	Capacitance (µF)
4S	1	2.01
1S	2	4.65
2S	3	6.74
3S	4	7.18

E. Submarine cables

The lumped parameter line model was used to model the submarine cables. It was considered that the circuit connecting FPSO 1 and 2 is formed by 3 three-core submarine cables connected in parallel with a cross-section of 630 mm², nominal voltage of 12/20 kV, and a length of 12 km. Table V shows the values of the electrical parameters of the cable model, based on a cable manufacturer's catalog [2].

TABLE V
ELECTRICAL PARAMETERS OF SUBMARINE CABLE MODEL

Electrical parameter	Value at 60 Hz
AC Resistance (Ω/km)	0.04195
Capacitive Reactance (Ω/km)	4583
Capacitance (µF/km)	0.578787
Inductive Reactance (Ω/km)	0.11370
Ampacity (A)	625

IV. DEFINITION OF GROUND FAULT SCENARIOS IN THE INTERCONNECTED SYSTEM OF THE FPSOs AND RESULTS

It is necessary to define the scenarios of ground fault events in the interconnected system before presenting the results.

A. Definition of ground fault event scenarios

The following scenarios 1A, 1B, 2A, 2B, 1AZZX, 1BZZX, 2AZZX and 2BZZX are defined.

Scenario 1A: Initial conditions resulting from the operation of 3 generators in FPSO 1 and 4 generators in FPSO 2 and a bolted ground fault event on the 13.8 kV panel of FPSO 1, with the grounding system unchanged.

Scenario 1B: Initial conditions resulting from the operation of 3 generators in FPSO 1 and 0 generators in FPSO 2 and a bolted ground fault event on the 13.8 kV panel of FPSO 1, with the grounding system unchanged. This scenario simulates the FPSO 1 with the subsea cables before the connection with FPSO 2.

Scenario 2A: Initial conditions resulting from the operation of 4 generators in FPSO 1 and 4 generators in FPSO 2 and a bolted ground fault event on the 13.8 kV panel of FPSO 1, with the grounding system unchanged.

Scenario 2B: Initial conditions resulting from the operation of 4 generators in FPSO 1 and 0 generators in FPSO 2 and a bolted ground fault event on the 13.8 kV panel of FPSO 1, with the grounding system unchanged. This scenario simulates the FPSO 1 with the subsea cables before the connection with FPSO 2.

Scenario 1AZZX: Identical scenario to scenario 1A, but with the use of 1 zig-zag transformer with a 150 A reactor on FPSO 1 and 1 zig-zag transformer with a 150 reactor on FPSO 2 in standby.

Scenario 1BZZX: Identical scenario to scenario 1B, but with the use of 1 zig-zag transformer with a 150 A reactor on FPSO 1 and 1 zig-zag transformer with a 150 reactor on FPSO 2 in standby.

Scenario 2AZZX: Identical scenario to scenario 2A, but with the use of 1 zig-zag transformer with a 150 A reactor on FPSO 1 and 1 zig-zag transformer with a 150 reactor on FPSO 2 in standby.

Scenario 2BZZX: Identical scenario to scenario 2B, but with the use of 1 zig-zag transformer with a 150 A reactor on FPSO 1 and 1 zig-zag transformer with a 150 reactor on FPSO 2 in standby.

B. Calculation of the maximum ground fault current for the interconnected units with the FPSO grounding systems unchanged

In Table VI, the results of the values of the ground fault current for scenarios 1A, 1B, 2A and 2B as defined in IV, are shown. These calculations were obtained through a simulation tool of mid-term and long-term transients using a renowned software in the electrical systems field.

TABLE VI
TOTAL FAULT CURRENT RESULTS - INTERCONNECTED OPERATION BETWEEN FPSOs 1 AND 2 WITH ORIGINAL GROUNDING SYSTEMS

Scenario	Total fault current
1A	189
1B	193
2A	183
2B	181

The maximum magnitude of the ground fault current must be assessed in conjunction with the fault clearing time of the units. From the pair of current and fault clearing time values, the damage curve of electrical machines should be used to evaluate the severity of damage when a ground fault occurs.

Regarding current and time, considering a fault clearing time of 100 ms, the pair values of maximum current and time are 193 A and 100 ms. This value of 100 ms corresponds to the sum of the protection adjustment of the 67N or 50GS function of the medium voltage machines, the processing time of the relays, the opening time of the medium voltage circuit breakers, and the arc extinction time.

Regarding the damage curve, Fig. 4 shows the damage curve of the magnetic package for each of the 4 electric generators of FPSO 1 and the 4 electric generators of FPSO 2, available in project documents.

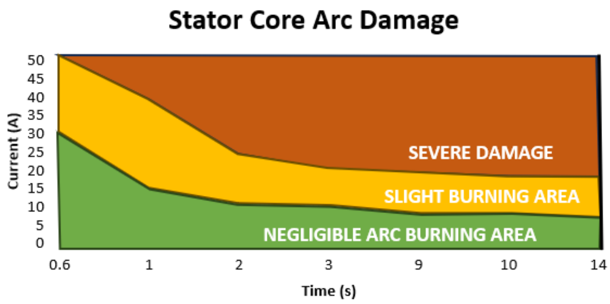

Fig. 4 Damage curve of the generators of FPSOs 1 and 2

With the curve from Fig. 4 and the pair of values of 193 A and 100 ms, it is not possible to assert with confidence that the internal damage to the machine will be severe or minor, since the maximum current shown on the graph is 50 A, and the time scale is not in milliseconds. Therefore, the generator manufacturer was asked to provide the extended damage curve for damage assessment; however, this request was unsuccessful. Without the manufacturer's information, the risk of severe damage to the magnetic package in the event of an internal fault cannot be ruled out and should be considered possible.

However, as an alternative, through the equation $I^2t = 1600$, an unofficial extended severe damage curve was created, as shown in Fig. 5, between the orange and yellow regions. This extended curve is presented in Fig. 5, and to illustrate, the point (I,t) = (40 A, 1 s) lies on it and also on the curve between the orange and yellow regions in Fig. 4.

Analyzing the position of the point (I,t) = (193 A, 100 ms) in Fig. 5, shown with a red dot, it is possible to conclude that the operation of the interconnected system between FPSOs 1 and 2 can cause severe damage to the generator when a ground fault occurs within it. Therefore, it would not be possible to operate the interconnected system without making changes to the grounding system to reduce the maximum ground fault current.

Also, in Fig. 5, it is possible to verify the maximum admissible ground fault current of 126.5 A associated with a fault clearing time of 100 ms.

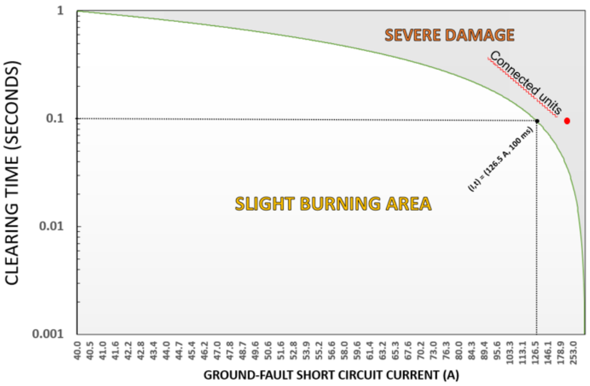

Fig. 5 Extended unofficial severe damage curve with the operating point at a current of 193 A

It is important to emphasize that the unofficial curve created from the equation $I^2t = 1600$ can be considered a conservative curve. This is justified through examples of damage curves of magnetic sheets from the stators of generators and motors from other manufacturers in different FPSO projects. For example, some curves from other manufacturers indicate points such as (I,t) = (130 A, 200 ms) and (I,t) = (250 A, 140 ms), whose I^2t values are equal to 3380 and 8750, respectively, which are greater than the value of 1600 A.

C. Evaluation of transient overvoltages based on the criteria IN/3Ic ≥ 0.7 and 3Ic/IL ≥ 0.6 for interconnected units with unchanged grounding system

The IN/3Ic and 3Ic/IL ratios for scenarios 1A, 1B, 2A and 2B were calculated to assess the transient overvoltages during the occurrence of an intermittent ground fault. The calculations were performed using an Excel spreadsheet for support.

The evaluation of these parameter were derived from the conclusions of paper [4], which stated that IN (sum of the currents in the neutrals) must be greater or equal to 70% of 3Ic (total capacitive current) and 3Ic must be greater or equal to 60% of IL (total inductive current) to limit the transient overvoltages, during the occurrence of an intermittent ground fault, to the maximum of 260%.

Tables VII, VIII, IX and X present the results of IN/3Ic and 3Ic/IL for scenarios 1A, 1B, 2A and 2B, respectively.

TABLE VII
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 1A

Component	Value
Capacitive component FPSO 1	68.8 A
Capacitive component FPSO 2	64.7 A
Capacitive component (Cable)	187.8 A
Total capacitive component	321.2 A
Total resistive component	96 A
Total inductive component	157.9 A
Total neutral current	184.8 A
IN/3Ic	0.58
3Ic/IL	2.03

TABLE VIII
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 1B

Component	Value
Capacitive component FPSO 1	68.8 A
Capacitive component FPSO 2	0 A
Capacitive component (Cable)	187.8 A
Total capacitive component	256.5 A
Total resistive component	41.1 A
Total inductive component	67.7 A
Total neutral current	79.2 A
IN/3Ic	0.31
3Ic/IL	3.79

TABLE IX
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 2A

Component	Value
Capacitive component FPSO 1	74.8 A
Capacitive component FPSO 2	64.7 A
Capacitive component (Cable)	187.8 A
Total capacitive component	327.2 A
Total resistive component	109.7 A
Total inductive component	180.5 A
Total neutral current	211.2 A
IN/3Ic	0.65
3Ic/IL	1.81

TABLE X
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 2B

Component	Value
Capacitive component FPSO 1	74.8 A
Capacitive component FPSO 2	0 A
Capacitive component (Cable)	187.8 A
Total capacitive component	262.5 A
Total resistive component	54.9 A
Total inductive component	90.2 A
Total neutral current	105.6 A
IN/3Ic	0.40
3Ic/IL	2.91

Tables VII, VIII, IX and X show that the IN/3Ic values are all lower than 0.7 and thus the electrical interconnection between FPSOs 1 and 2, while maintaining their original grounding systems, may cause dangerous transient overvoltages during the occurrence of an intermittent ground fault.

Therefore, it is necessary to modify the grounding system of the interconnected system so that the ground fault current is lower, to avoid severe damage to the machines, and to satisfy the transient overvoltage criterion.

D. *Calculation of the maximum short-circuit current for interconnected units with ZigZag-X grounding system*

To reduce ground fault currents and control transient overvoltages, a modification of the grounding system is proposed when there is interconnection between the units. The proposal consists of adding a connection of a Zig-Zag transformer with a neutral reactor with an impedance of 53.116 Ohms (150 A) to busbar B of the 13.8 kV panel of FPSO 1, and a connection of the same transformer and reactor to busbar A of the 13.8 kV panel of FPSO 2 working as backup equipment. It should be noted that these new devices can be connected to new 13.8 kV panels that may be necessary for the interconnection. Fig. 6 shows a drawing of the transformer solution and its reactor, while Fig. 7 shows the simplified diagram of the interconnected electrical system with the connection of these two Zig-Zag transformers with their reactors.

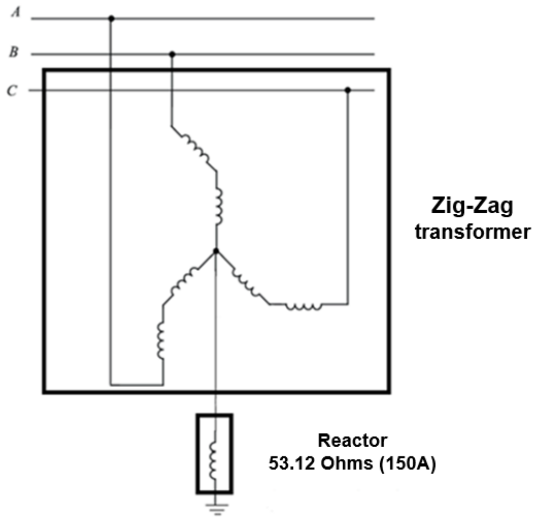

Fig. 6 Zig-Zag Transformer + Reactor on FPSO 1 and 2

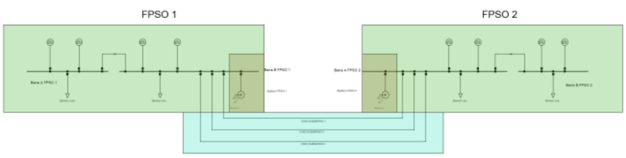

Fig. 7 Simplified diagram of the interconnected system with Zig-Zag transformers and their reactors (one equipment works as standby)

In this case, one of the two Zig-Zag transformers with their reactors would only be connected when both FPSOs are connected. When the FPSOs are operating independently, both transformers would remain disconnected.

Table XI shows the results of the ground fault current values for scenarios 1AZZX, 1BZZX, 2AZZX and 2BZZX, which were defined in IV. These calculations were obtained through a simulation tool of mid-term and long-term transients using a renowned software in the electrical systems field.

TABLE XI
TOTAL FAULT CURRENT RESULTS - INTERCONNECTED OPERATION BETWEEN FPSOs 1 AND 2 – ZIG-ZAG TRANSFORMERS WITH REACTORS

Scenario	Total fault current
1AZZX	97
1BZZX	57
2AZZX	110
2BZZX	59

The maximum ground fault current became 110 A with the use of this solution. Thus, in Fig. 8, the new location of the point (I,t) is shown in green. It is possible to see the position of the new point, with the modified grounding system, which has moved from the initial point with a current of 193 A, without a change in the grounding system.

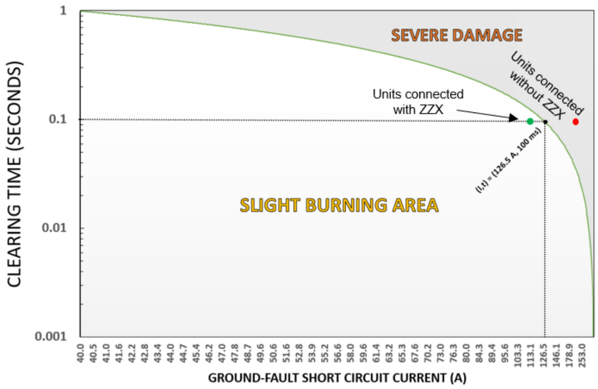

Fig. 8 Extended unofficial severe damage curve with the new operating point at a current of 110 A

In Fig. 8, it is evident that the current point of 110 A stays in the area of slight burning area demonstrating the correct choice of the reactor size.

E. *Evaluation of transient overvoltages based on the criteria IN/3Ic ≥ 0.7 and 3Ic/IL ≥ 0.6 for interconnected units with ZigZag-X grounding system*

The IN/3Ic and 3Ic/IL ratios for scenarios 1AZZX, 1BZZX, 2AZZX and 2BZXX were calculated to assess the transient overvoltages during the occurrence of an intermittent ground fault. The calculations were also performed using an Excel spreadsheet for support.

Tables XII, XIII, XIV and XV present the results of IN/3Ic and 3Ic/IL for scenarios 1AZZX, 1BZZX, 2AZZX and 2BZZX, respectively.

TABLE XII
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 1AZZX

Component	Value
Capacitive component FPSO 1	68.8 A
Capacitive component FPSO 2	64.7 A
Capacitive component (Cable)	187.8 A
Total capacitive component	321.2 A

Total resistive component	96 A
Total inductive component	307.9 A
Total neutral current	322.5 A
IN/3Ic	1.00
3Ic/IL	1.04

TABLE XIII
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 1BZZX

Component	Value
Capacitive component FPSO 1	68.8 A
Capacitive component FPSO 2	0 A
Capacitive component (Cable)	187.8 A
Total capacitive component	256.5 A
Total resistive component	41.1 A
Total inductive component	217.7 A
Total neutral current	221.5 A
IN/3Ic	0.86
3Ic/IL	1.18

TABLE XIV
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 2AZZX

Component	Value
Capacitive component FPSO 1	74.8 A
Capacitive component FPSO 2	64.7 A
Capacitive component (Cable)	187.8 A
Total capacitive component	327.2 A
Total resistive component	109.7 A
Total inductive component	330.5 A
Total neutral current	348.2 A
IN/3Ic	1.06
3Ic/IL	0.99

TABLE XV
RESULTS OF IN/3Ic AND 3Ic/IL – SCENARIO 2BZZX

Component	Value
Capacitive component FPSO 1	74.8 A
Capacitive component FPSO 2	0 A
Capacitive component (Cable)	187.8 A
Total capacitive component	262.5 A
Total resistive component	54.9 A
Total inductive component	240.2 A
Total neutral current	246.4 A
IN/3Ic	0.94
3Ic/IL	1.09

Tables XII, XIII, XIV and XV show that the IN/3Ic values are all greater than 0.7 and 3Ic/IL are all greater than 0.6, thus the electrical interconnection between FPSO 1 and 2, adding the Zig-Zag transformers with reactors, would not generate dangerous transient overvoltages during the occurrence of an intermittent ground fault. In addition to this positive characteristic, this grounding solution also led to a maximum short-circuit current of 110 A, which is suitable for a fault clearing time of 100 ms, as shown in Fig. 8.

VI. ELETROMAGNETIC TRANSIENTS RESULTS

Some simulations were performed using ATP to visualize the voltage waveforms during the intermittent ground fault and to visualize the currents waveforms during a bolted ground fault. These results were obtained for Scenario 1B and 1BZZX.

The electrical diagram used to obtain the graphics was the same as the paper [4] and it is shown in Figure 9.

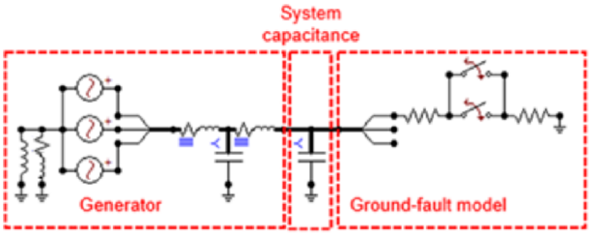

Fig. 9 Electrical diagram used to obtain the transient waveforms in ATP.

The results of the voltage waveforms during an intermittent ground fault for Scenario 1B and 1BZZX are shown in Figure 10 and Figure 11, respectively.

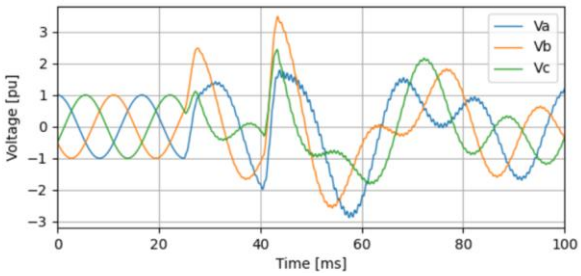

Fig. 10 Voltage waveforms of Scenario 1B during an intermittent ground fault.

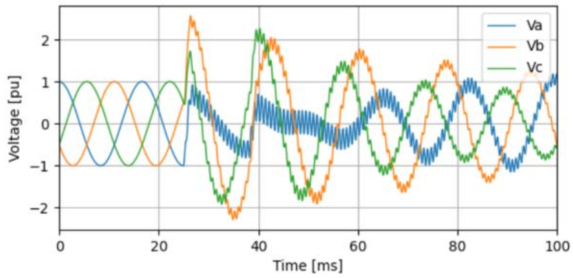

Fig. 11 Voltage waveforms of Scenario 1BZZX during an intermittent ground fault.

The results shown in Figures 10 and 11 show that the maximum overvoltage reduced from 3.5 pu to 2.56 pu demonstrating that the solution of hybrid resistive-inductive grounding through the ziz-zag transformer with reactor was a suitable proposal.

The results of the current waveforms during a bolted ground fault for Scenario 1B and 1BZZX are shown in Figure 12 and Figure 13, respectively.

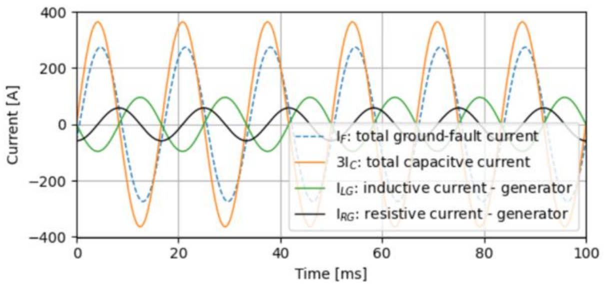

Fig. 12 Current waveforms of Scenario 1B during a bolted ground fault.

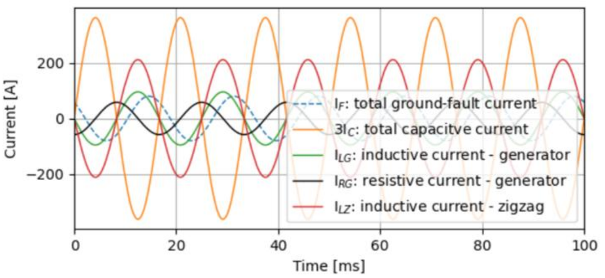

Fig. 13 Voltage waveforms of Scenario 1BZZX during a bolted ground fault.

The results shown in Figures 12 and 13 show that the maximum RMS total ground fault current reduced from 193 A to 57 A demonstrating that the solution of hybrid resistive-inductive grounding through the zig-zag transformer with reactor was a suitable proposal.

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V. CONCLUSIONS

This paper examined ground fault events in an interconnected system involving two FPSOs utilizing three submarine cables with a maximum transmission capacity of 30 MVA at 13.8 kV. The findings revealed that operating the interconnected units without modifications to their grounding systems could result in high ground fault short-circuit currents and potentially hazardous transient overvoltages.

However, it was shown that the use of hybrid resistive-inductive grounding, such as the combination of the existing grounding method of the FPSOs together with a complementary grounding using a zig-zag transformer with a reactor, could be a solution to limit the damage in stator core of the machines and to control the overvoltages to levels below 2.6 pu.

This grounding solution is well-suited for the interconnection of the two FPSOs at 13.8 kV, offering significant advantages such as minimizing topside modifications, enhancing transmission reliability, and enabling the use of more mature technology subsea cables.

VI. REFERENCES

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VII. VITA

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