EFFECTS OF MAGNETIC CORE CONFIGURATION AND SATURATION IN EARTHING TRANSFORMERS

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Abstract – Resistive earthing of Medium Voltage systems has been proven beneficial in limiting fault currents during ground faults and suppressing resonance and surge voltage conditions, which are crucial for safe operation. Earthing can be achieved directly at power generators, through power transformers, or by means of dedicated earthing transformers. This paper investigates the impact of magnetic core saturation in earthing transformers by examining real cases on FPSO facilities where these transformers failed to perform as expected. Analysis of site data from disturbance recorders identified magnetic core configuration and core saturation as key issues due to incorrect design by the manufacturer. The findings highlight the importance of rigorous engineering and testing practices in the design of earthing transformers to ensure optimal performance.

Index Terms — Resistive Earthing, Medium Voltage (MV) Systems, Ground Fault, Earthing Transformers, Magnetic Core Saturation, Engineering Practices, Testing Practices, FPSO.

NOMENCLATURE

MV Medium Voltage
LV Low Voltage
FPSO Floating Production Storage and Offloading
NER Neutral Earthing Resistor
ETR Earthing Transformer
IED Intelligent Electronic Device (Protection Relay)

I. INTRODUCTION

In offshore electrical installations, the safety and reliability of the power system are fundamental. One critical aspect of this is the effective management of ground fault currents [1][2][4], which can pose significant risks to both equipment and personnel. Resistive earthing of medium voltage (MV) systems has been proven beneficial in limiting fault currents during ground faults and suppressing resonance and surge voltage conditions.

Different earthing schemes are possible: earthing at the power generator star center, earthing at the power transformer, or using dedicated earthing transformers. While all these solutions are effective, the latter is more flexible and safer. Allowing current to pass through the generators' windings can be harmful, and most power transformers are designed with a 3-limb core for economic reasons, which has a closing path for zero-sequence flux external to the core [6]. Dedicated earthing transformers, on the other hand, are purpose-designed and provide isolation between the MV system and the ground.

With these concepts in mind, the paper is structured as follows: Section II reports the typical earthing scheme for FPSO installations and the sizing of earthing transformers and resistors; Section III presents real cases in similar installations where, upon earth faults, the transformers failed to perform as expected, and investigates the failures, identifying issues in the magnetic core configuration and saturation during earth faults that could have been detected with proper factory testing.

II. EARTHING SCHEME IN ALL ELECTRIC FPSO

Depending on field specificities, newly designed FPSOs may exhibit a total load demand of 70 MW to 120 MW during normal production [3]. Figure 1 shows a typical MV single line diagram. It includes two interconnected systems at 11 kV: one dedicated to the Topside, with Gas Generation, and the other to the Hull, with Essential Generation (Diesel). Dedicated bus links interconnect the systems. Both systems can run, to a certain extent, independently.

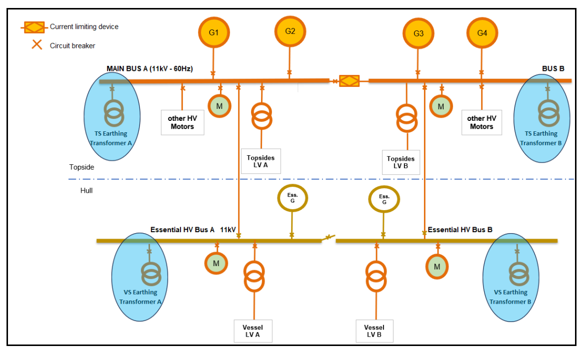

Fig. 1. MV typical single line diagram

The system is designed for modularity, allowing the two MV networks to be installed at different times and integrated later. For this reason, each bus is provided with a dedicated earthing transformer equipped with Neutral Earthing Resistor (NER). The Earthing Transformers (ETR) have wye-neutral configuration on the MV side, with the secondary open delta closed on the NER at low voltage (LV) (see Figure 2).

NER sizes are calculated for the Hull, considering its own capacitive current, and for Topside, considering the overall capacitive current of the FPSO (Topside and Hull), following IEC 60287-1-1 [5].

During normal operations, Topside 11kV system works with the bus-tie closed, while Hull 11kV system operates with the bus-tie opened. The Topside-Hull links are both closed. For operational reasons, including the simplification of automatic logics in case of network separation, one Topside and one Hull earthing transformer are connected to guarantee an earthing reference to the system.

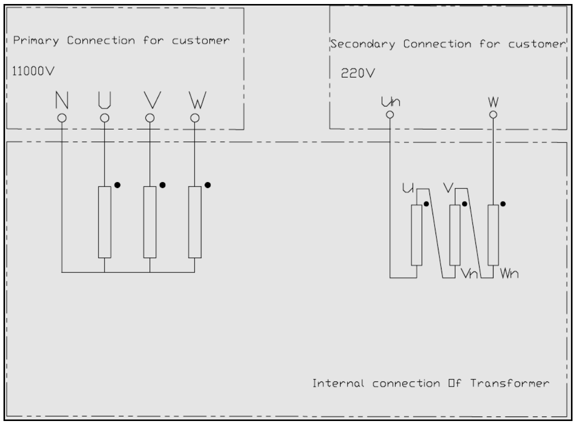

Fig. 2. Earthing Transformers Wiring

III. REAL CASES: EARTH FAULTS AND SYSTEM RESPONSE

With the above scheme in place, any earth fault current should be limited to the desired value. During normal operation, with Topside and Hull systems connected, the earth fault current should result, in case of bolted earth fault, in the sum of the current reclosed by the connected earthing transformers.

In the analyzed cases, on two twin FPSOs, bolted earthing currents of Topside and Hull are limited by the related NER to respectively to 63A and 10A.

A. Introduction

As anticipated in Section II, in normal operations the FPSO works with both Topside and Hull 11kV system interconnected. The MV distribution of FPSO is designed to maintain the highest reliability in case of failures. All different feeder types, such as alternators incomers, motors feeders, transformers feeders and distribution feeders (links), are equipped with Intelligent Electronic Devices (IEDs) to protect the individual feeder and connected equipment/subsystem.

Earthing transformers are connected to the MV switchboards by typical “fuses+contactor” feeder scheme, as indicated in Figure 3 (Topside) and Figure 4 (Hull). Fuses (for short-circuit) and the IED functions 26 (internal temperature protection), 50/51 (overcurrent), and 51N (earth fault) ensure protection. The 51N function selectively discriminates real earth faults in the transformer from earth faults elsewhere in the network, which are protected by feeder dedicated overcurrent protection 50G.

Characteristics of the earthing transformers connected to the MV network under analysis are reported in Table I (Topside Earthing Transformer Datasheet) and Table II (Hull Earthing Transformer Datasheet). The next sections will present two incidents out of the six earth fault cases experienced in six motors failures affected by manufacturing defects in two twin FPSOs.

B. Incidents Descriptions and Sequence of Events

1) Incident 1: offloading pump motor earth fault on FPSO-1

Network configuration is visible in Figure 5. The FPSO was running with three gas turbines connected at Topside with links to the Hull closed. Topside Earthing Transformer under bus B and Hull Earthing Transformer under bus A were connected.

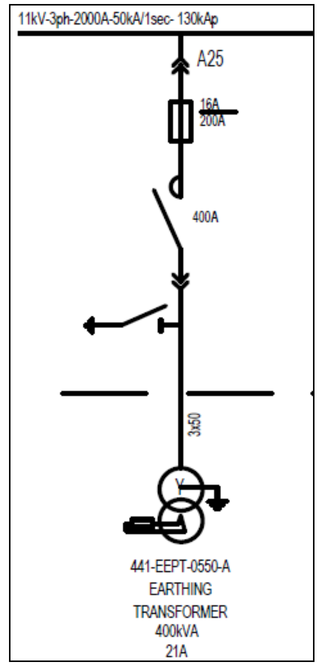

Fig. 3. Topside Earthing Transformer connection

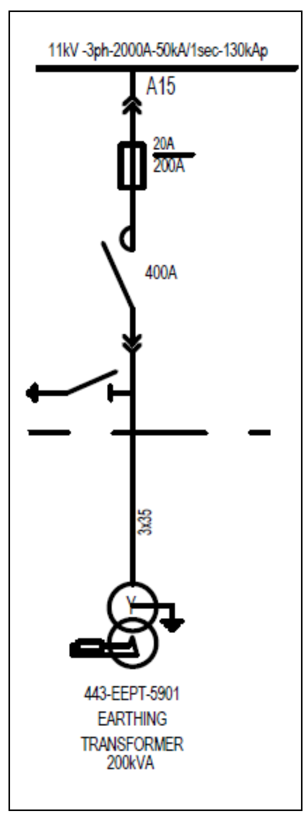

Fig. 4. Hull Earthing Transformer connection

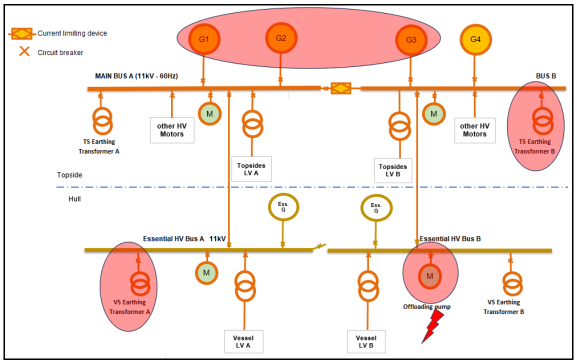

Fig. 5. Incident 1 – Single Line Diagram reference

The bus-tie at Hull MV switchboard was open. The failed offloading pump motor was connected under bus B of the Hull. During the inrush of the offloading pump motor, phase L3 failed. The expected fault current was 73A (63A reclosing on Topside Transformer and 10A reclosing on Hull Transformer). However, the actual fault current reached about 280A, with 57A from the Topside Earthing Transformer (Figure 7.a.) and about 240A from the Hull Earthing Transformer (Figure 7.b.). The phase displacement between the earth fault current and zero-sequence voltage was about 65 degrees (1.135 rad), as indicated in Figure 7.c.

TABLE I
DATA-SHEET OF TOPSIDE EARTHING TRANSFORMER

	Primary winding		*Secondary winding*
No. of phases	3		3
Rating AN	400kVA during fault (21A per phase @ 11kV) for 10 seconds. 5A continuous current per phase on 11kV side		
Rated voltage	11kV (ph-ph)		230V (phase)
Connections	Wye		Delta (Open)
Maximum system voltage	12kV		1.1kV
Power frequency withstand	28kV		3kV
BIL (kV)	75kV		-
Winding material	Copper		Copper
Insulation type	Cast resin		VPI impregnated
Insulation Temperature Class	F		H
Temperature rise limit	F		F
NER size	-		1.2 ohm
Earth fault current	63A (21A per phase)		-
No load losses	0.8kW	*Ambient temperature*	45degC
Load losses (120 degC)	1.5kW (@ 95.23kVA)	*Enclosure IP*	IP23
Impedance voltage	6.5% (approx. @ 95.23kVA)	*Cooling*	AN
Vector group	YNd OPEN	*Installation*	Indoor
Frequency	60 Hz		

2) Incident 2: sea water lift pump motor earth fault on FPSO-2

The network configuration is visible in Figure 6. The FPSO was running with three gas turbines connected at Topside with links to the Hull closed. Topside Earthing Transformer under bus B and Hull Earthing Transformer under bus A were connected.

TABLE II
DATA-SHEET OF HULL EARTHING TRANSFORMER

	Primary winding		*Secondary winding*
No. of phases	3		3
Rating AN	200kVA during fault (10.5A per phase @ 11kV) for 10 seconds. 3A continuous current per phase on 11kV side		
Rated voltage	11kV (ph-ph)		220V (phase)
Connections	Wye		Delta (Open)
Maximum system voltage	12kV		1.1kV
Power frequency withstand	28kV		2.4kV
BIL (kV)	75kV		-
Winding material	Copper		Copper
Insulation type	Cast resin		Cast resin
Insulation Temperature Class	F		F
Temperature rise limit	F		F
NER	-		6.9 ohm
Earth fault current	10A (3.3A per phase)		-
No load losses	1.1kW	*Ambient temperature*	45degC
Load losses (95 degC)	2.9kW	*Enclosure IP*	IP23
Impedance voltage	3.5% (0~+10%)	*Cooling*	AN
Vector group	YNd OPEN	*Installation*	Indoor
Frequency	60 Hz		

The bus-tie at Hull MV switchboard was open. The failed sea water lift pump motor was connected under bus A of Topside.

During the inrush of the sea water lift pump motor, phase L3 failed. The expected fault current was 73A (63A from the Topside Transformer and 10A from the Hull Transformer). However, the actual fault current reached about 380A, with 56A from the Topside Earthing Transformer (Figure 8.a.) and above 350A from the Hull Earthing Transformer (Figure 8.b.). This caused fuse L1 to blow in two cycles (around 35ms) and the contactor to open. The earth current stabilized to about 56A after the disconnection of the Hull Earthing Transformer, as indicated in Figure 8.c.

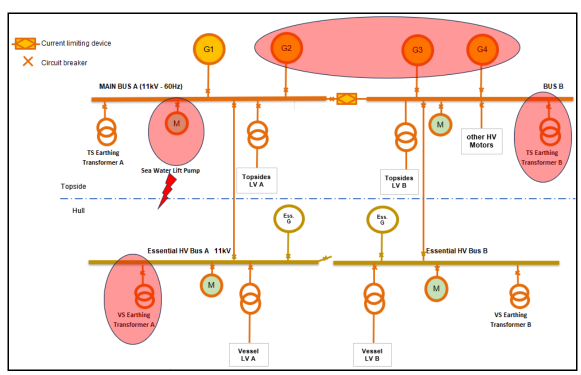

Fig. 6. Incident 2 – Single Line Diagram reference

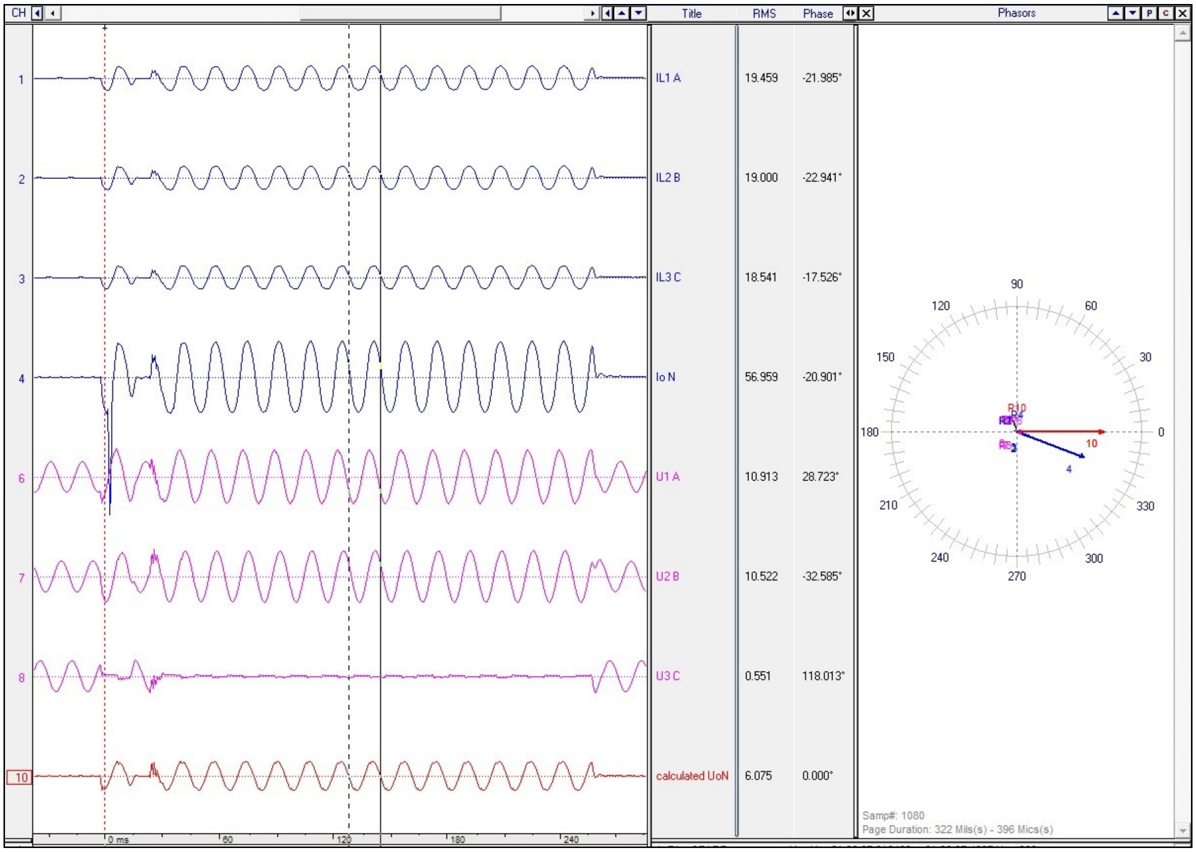

Fig. 7.a. Incident 1 – Topside Earthing Transformer Disturbance Recorder

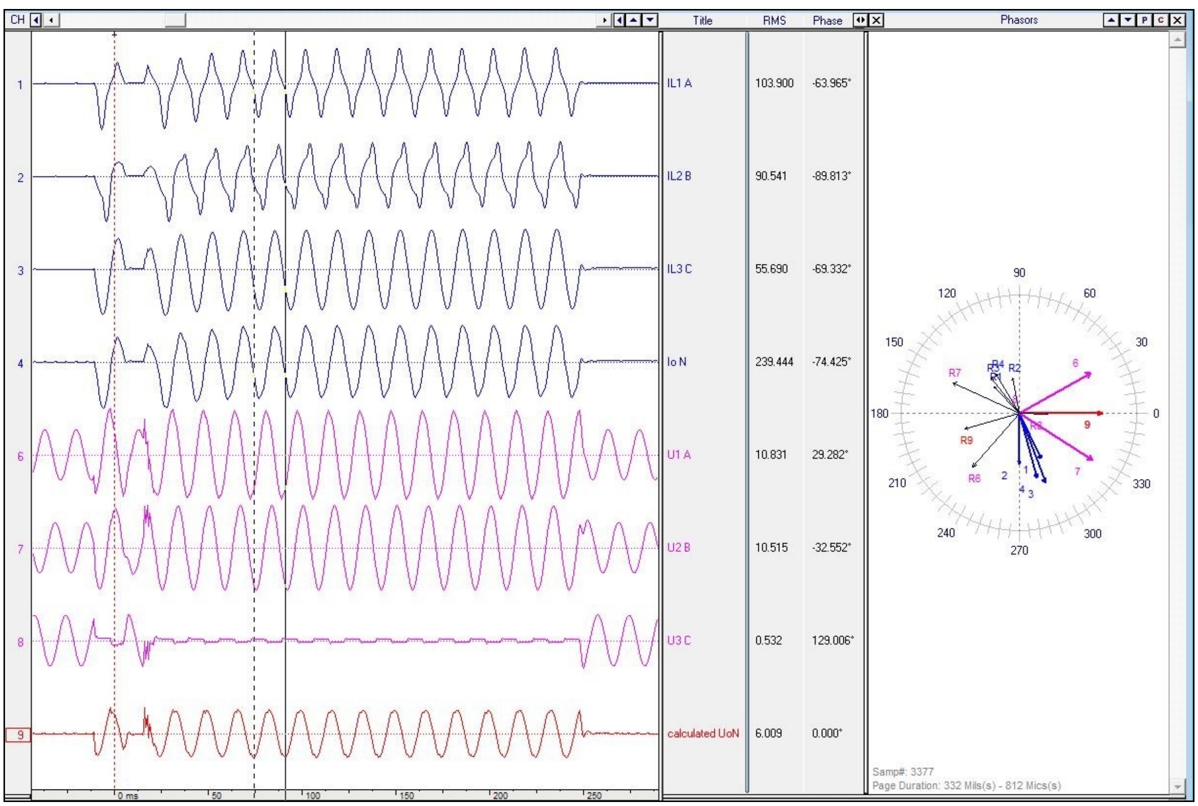

Fig. 7.b. Incident 1 – Hull Earthing Transformer Disturbance Recorder

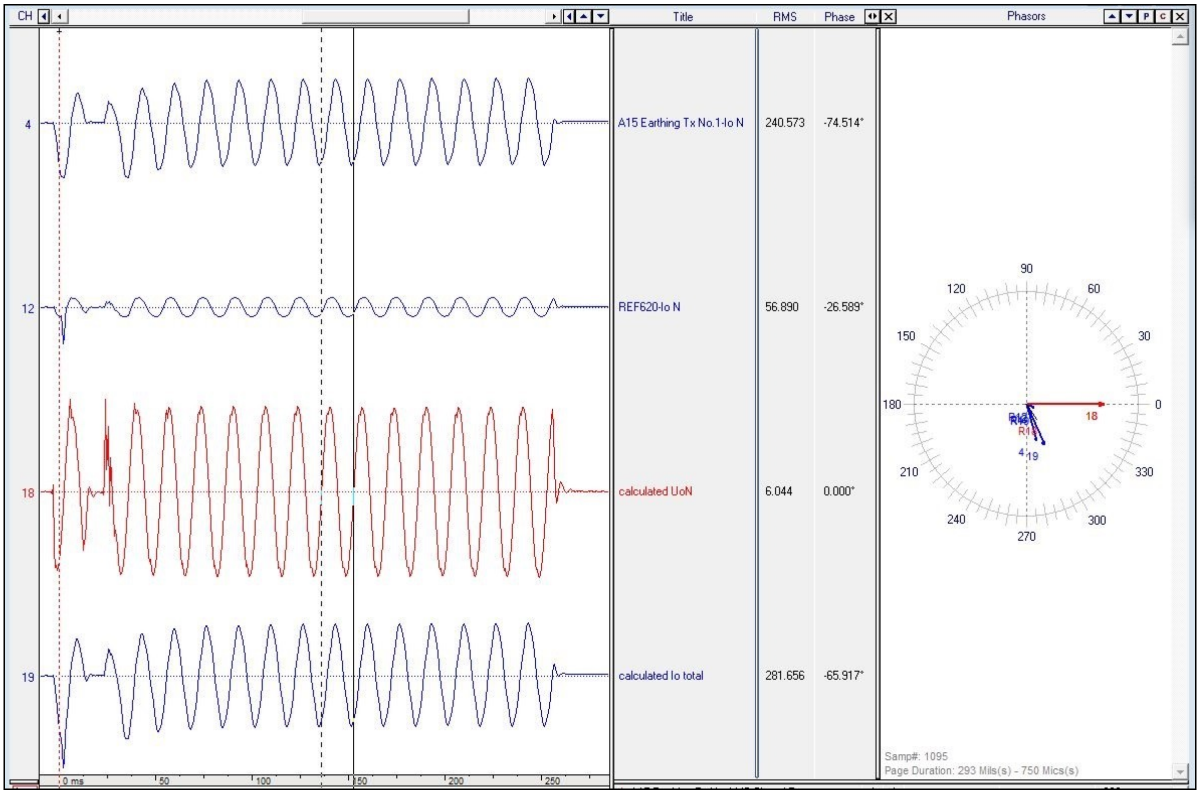

Fig. 7.c. Incident 1 – Overall Fault Disturbance Recorder (“A15 Earthing” indicates the Hull Earthing Transformer)

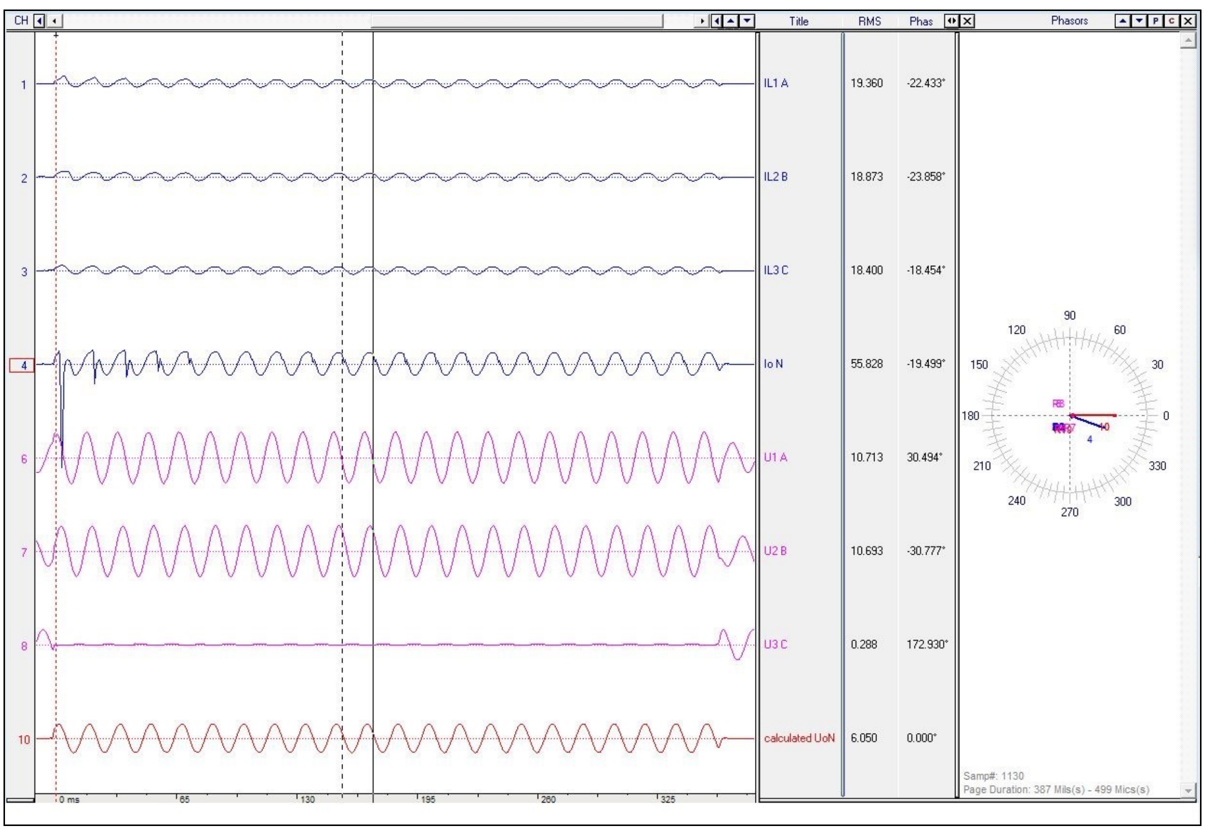

Fig. 8.a. Incident 2 – Topside Earthing Transformer Disturbance Recorder

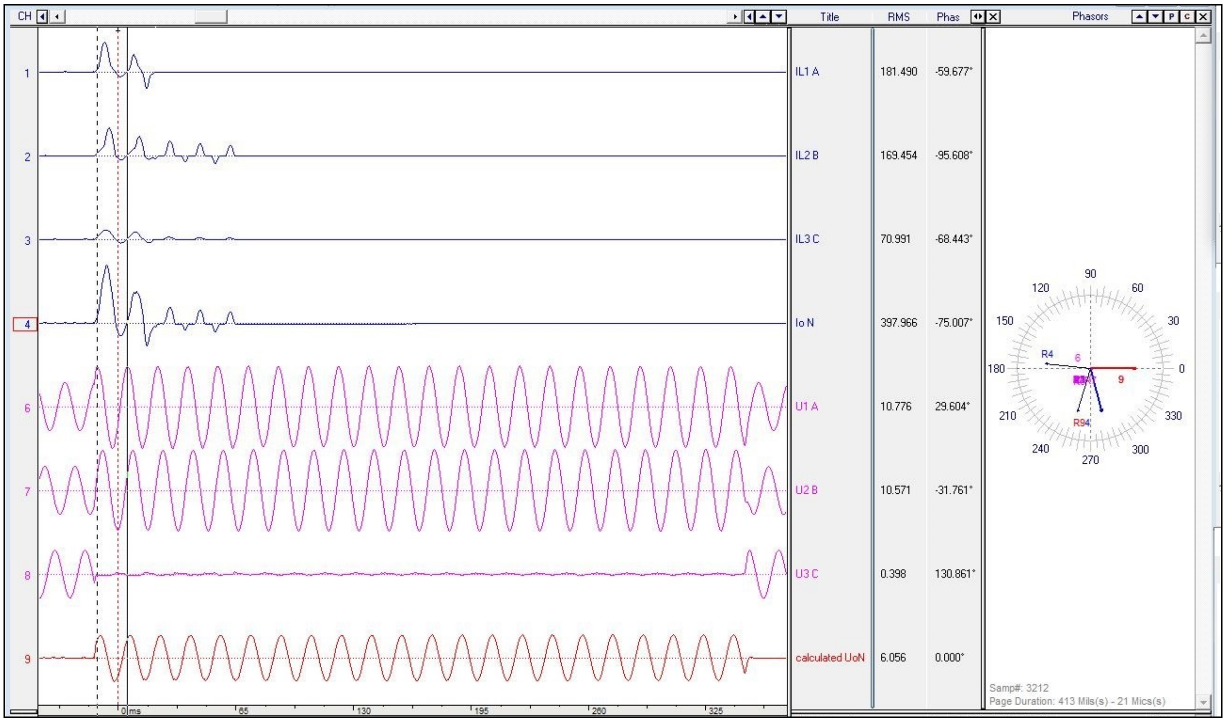

Fig. 8.b. Incident 2 – Hull Earthing Transformer Disturbance Recorder

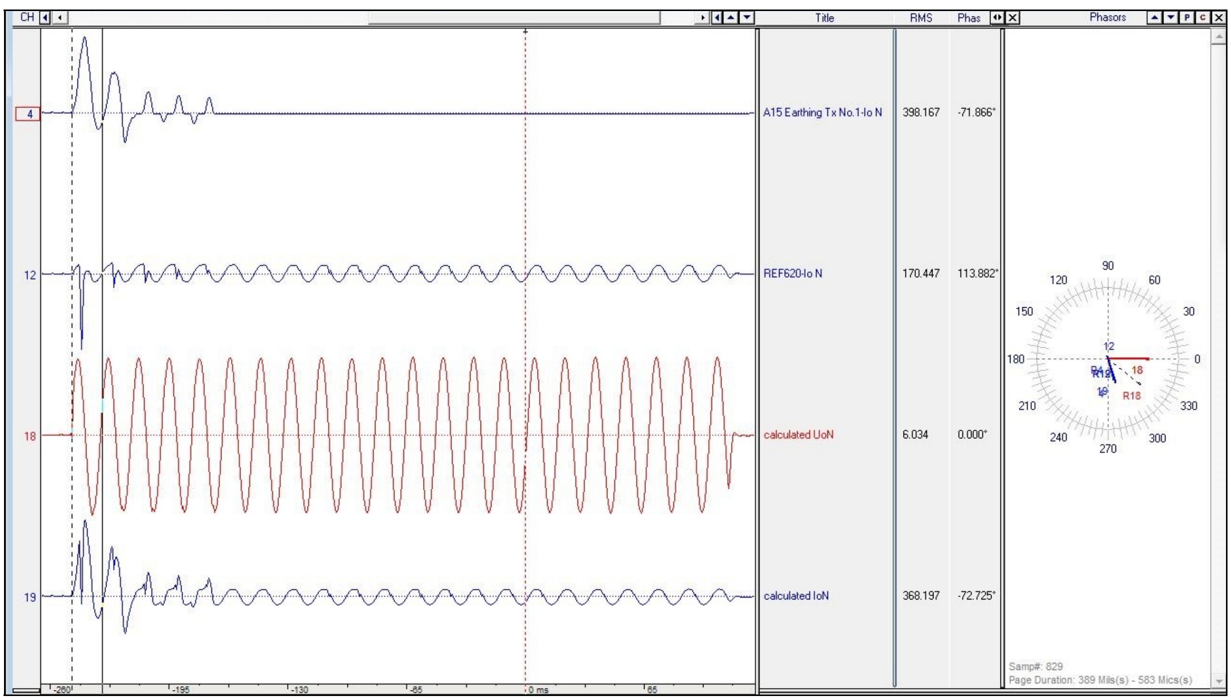

Fig. 8.c. Incident 2 – Overall Fault Disturbance Recorder ("A15 Earthing" indicates the Hull Earthing Transformer)

C. Design Assessment

The system response during earth faults did not meet the intended design. While Topside Earthing Transformer response was within the limits and proportional to the zero-sequence voltage, the Hull Earthing Transformer earth current was extremely high, causing a fuse to blow in one case.

The first incident investigation focused mainly on the failed motor. The second incident, occurring more than six months later on a different installation, highlighted a common issue in the earth fault current. Additionally, the blown fuse on the Hull Earthing Transformer addressed the investigation in this direction.

After verifying the insulation resistance and connections on-site, with satisfactory results and no anomalies encountered, the first step was the design assessment of the earthing system. Simulations were carried out for the Hull Earthing System. Figure 9 shows the simulation results of the Hull Earthing Transformer with an NER of 6.9 ohms in an equivalent network

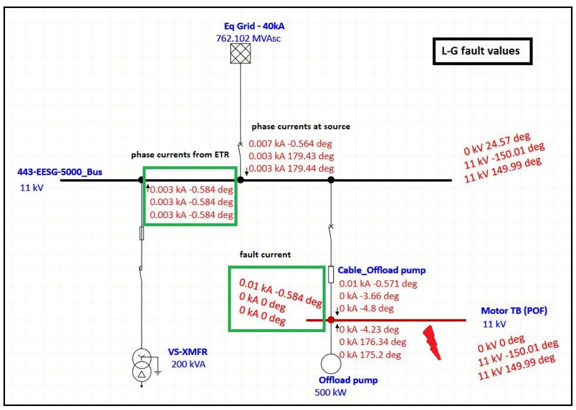

Fig. 9. Equivalent network – Hull Earthing Transformer with designed resistor

NER value was embedded into the Rcc% value of the earthing transformer as per equation (1):

$$R_{cc-zero\%} \approx R_{cc\%} + 100 \cdot S_n \cdot \frac{NER}{(3U_2)^2} \tag{1}$$

where

- $R_{cc\text{-}zero\%}$ zero-sequence equivalent resistance of windings;
- $R_{cc\%}$ equivalent resistance of windings for direct and inverse sequence;
- S_n earthing transformer rated power [MVA];
- U_2 earthing transformer rated secondary voltage [kV].

IT should be noted that above equation does not consider the transformer core configuration and magnetization, which instead played a crucial role in this case. The earthing transformer impedance for zero sequence reflect the values displayed on Figure 10.

The results confirm that the problem was not in the electrical circuit of the earthing transformer but in the magnetic core.

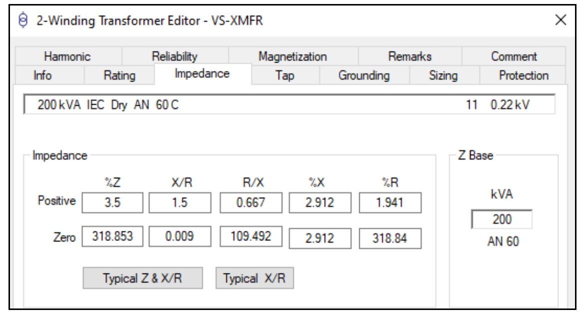

Fig. 10. Impedance of Hull Earthing Transformer

During inspection and documentation analysis, it was found that the transformer was manufactured with 3-limbs magnetic core, as reported in Figure 11.

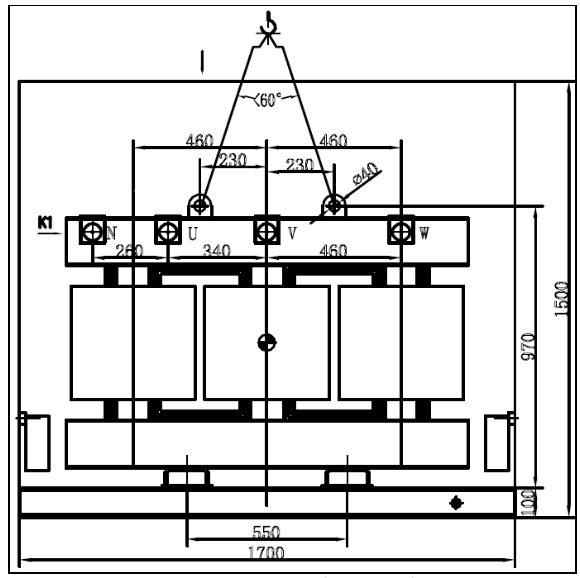

Fig. 11. Hull Earthing Transformer - Outline drawing

3-limbs core transformers are suitable for power transformers due to their reduced dimensions and weight. However, the zero-sequence impedance is limited compared to 5 limbs core transformers, due to the reclosing zero-sequence flux in air [8][9], as indicated in Figure 12 and equations (2) and (3).

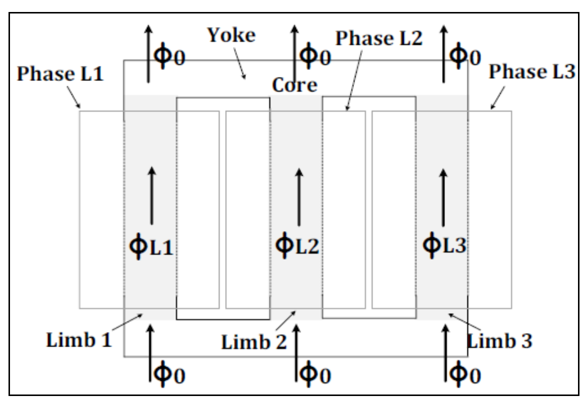

Fig. 12. 3-limb core transformer circuit

$$R_{mo} = R_{fe} + R_{air} = \frac{l_{fe}}{\mu_{fe} \cdot A_{fe}} + \frac{l_{air}}{\mu_{air} \cdot A_{air}} \approx \frac{l_{air}}{\mu_{air} \cdot A_{air}} \quad (2)$$

$$L_{mo} = \frac{N^2}{R_{mo}} \approx \frac{\mu_{air} \cdot A_{air} \cdot N^2}{l_{air}} \quad (3)$$

where

R_{mo}	zero-sequence magnetic reluctance
R_{fe}	magnetic reluctance of the core
R_{air}	magnetic reluctance of the air
μ_{fe}	permeability of the core
μ_{air}	permeability of the air
l_{fe}	equivalent length of core limb and yoke
l_{air}	equivalent length of air closing circuit
A_{fe}	equivalent cross section area of core
A_{air}	equivalent cross section area of air
L_{mo}	zero-sequence magnetic inductance

In 5-limbs core transformers, the reclosing of zero-sequence flux is in the external limbs of the core, resulting in a much higher zero-sequence inductance due to the higher permeability of the core.

The core-configuration has been identified as a root cause of the high current; however, a second step was reserved for the analysis of the disturbance recorders, presented in below section III.D.

D. Disturbance Recorders Analysis

After assessing the equipment design, remaining efforts were focused to the disturbance recorders.

With reference to Figures 7.a.b.c and Figures 8.a.b.c., the following anomalies were identified in the response of the Hull Earthing Transformer:

1) Earth current over 20-25 times the expected one.
2) Differences in phase currents, with major currents on the healthy phases (L1 and L2).
3) Angle between zero sequences voltage and earth current.
4) Distortion of currents waveform.

The currents harmonic contents for the Hull Earthing Transformer, for the two incidents, are reported in Figure 13.a.b. and Figure 14.a.b. respectively. Current distortion and phase imbalance at the Hull Earthing Transformer has been identified as effects of core saturation. The phase displacement between earth voltage and current (above 65 degrees) reinforces the finding, suggesting that the network is equivalently earthed with an inductive impedance. Moreover, the value and the harmonic distortion of the current of the faulted phase, which is almost negligible in the first incident, confirmed the assumption.

During the earth fault of one phase, the remaining healthy phases increase the voltage to the phase-to-phase level, as visible in Figure 15. The increase of voltage results in an increase of the magnetic flux, as per equations (4) and (5):

$$U_{ph1} = 4.44 \cdot N_1 \cdot k \cdot f \cdot \emptyset \quad (4)$$

$$\emptyset = B \cdot S \quad (5)$$

where

U_{ph1}	phase voltage on the winding [kV]
N_1	primary winding coils
k	construction constant [kV*m/(A*Hz)]
f	frequency [Hz]
$\emptyset$	magnetic flux [A/m]
B	magnetic induction [T]
S	magnetic core cross section [m2]

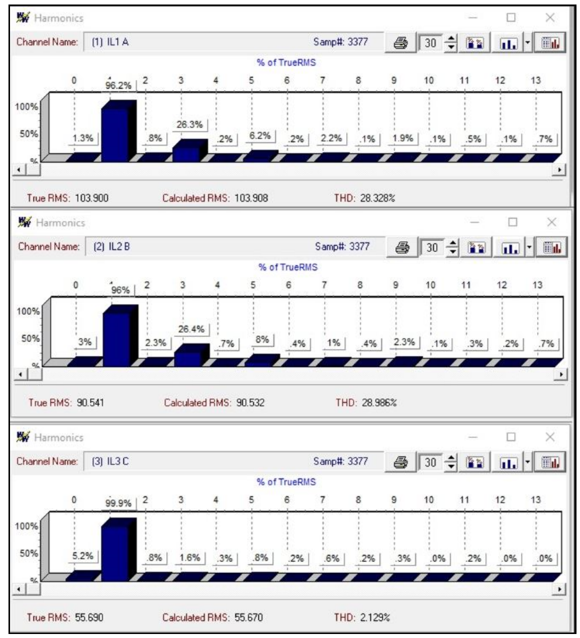

Fig. 13.a Incident 1 - Hull Earthing Transformer phase currents harmonics (failure phase L3)

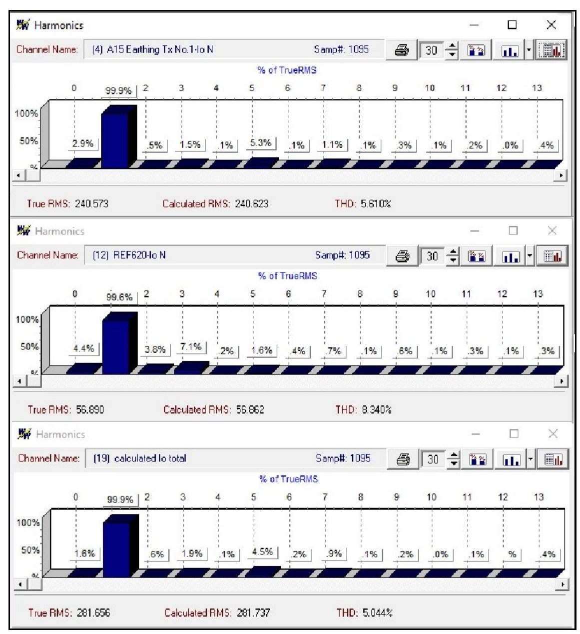

Fig. 13.b Incident 1 – Earth currents harmonics (channel(4) Hull ETR – channel(12) Topside ETR – channel(19) fault current)

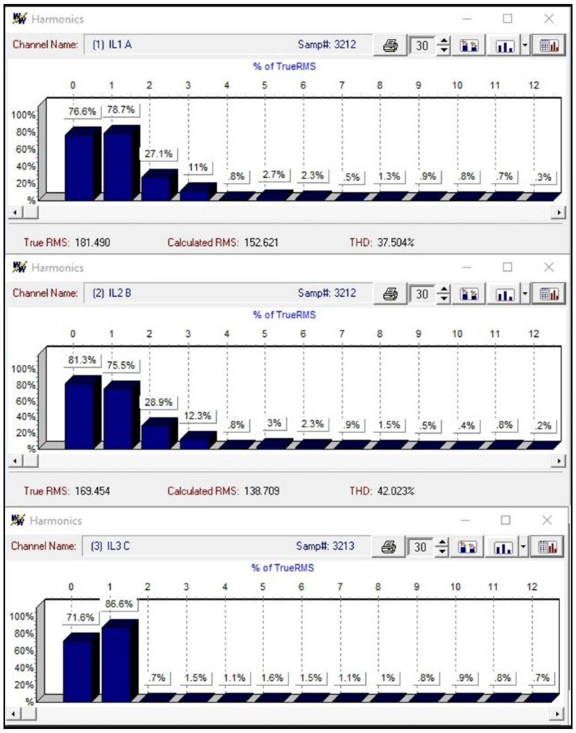

Fig. 14.a Incident 2 - Hull Earthing Transformer phase currents harmonics (failure phase L3)

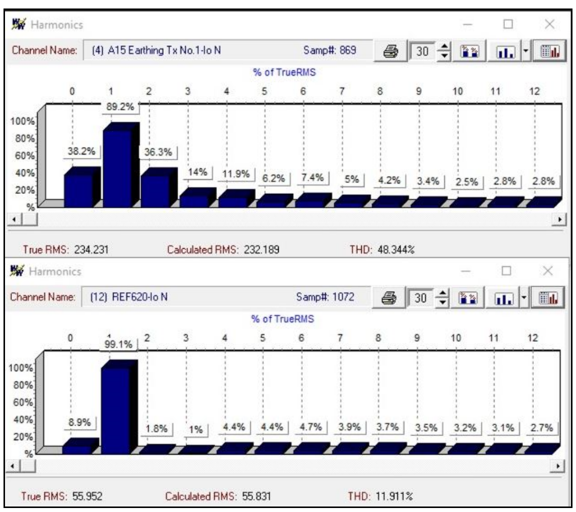

Fig. 14.b Incident 2 – Earth currents harmonics (channel(4) Hull ETR – channel(12) Topside ETR – fault current not reported (fuse at Hull ETR blown in 2 cycles)

E. Investigation Outcome and Lessons Learnt

It was assessed together with the manufacturer that the transformer was designed for power applications and not for earthing power systems. The design flaw was identified in the core geometry (3-limbs core) and the number of coils per phase. The area sections of the transformer core limbs and yokes were confirmed as correct.

Additional casual factors, identified in design review and incomplete testing, were also noted in the investigation.

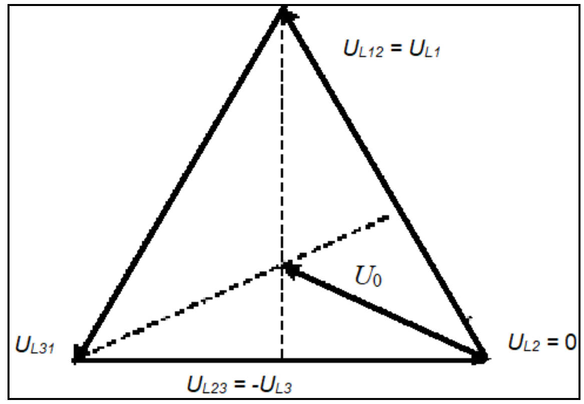

Fig. 15. Voltage diagram during earth fault in phase L2

A simple check of the core configuration in the transformer outline drawing can verify the zero-sequence impedance [6][7] at the factory. Prevention of core saturation can be assessed on transformers size calculation (if available from the manufacturer) or by testing of the earthing transformer at full voltage (phase-to-phase) on one phase. The two tests can be combined if the manufacturer has the necessary testing facilities. A reference scheme is reported in Figure 16.

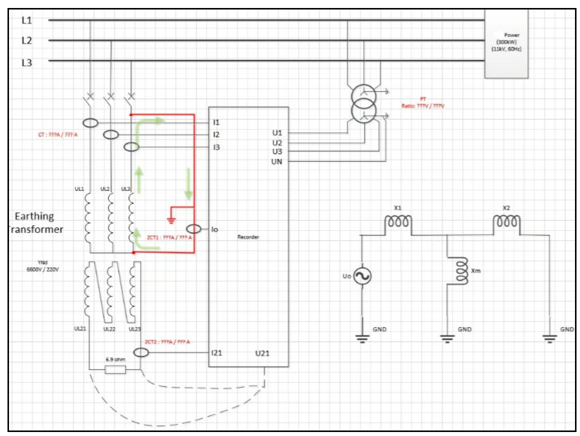

Fig. 16. Full voltage testing scheme.

Implementing these checks and tests will ensure that transformers are appropriately designed for earthing applications.

IV. CONCLUSIONS

The investigation into the earth faults and system response of the two FPSOs under subject revealed critical design flaws in the earthing transformers. The primary issue was identified in the core geometry, specifically the use of a 3-limb core, which is not suitable for earthing applications due to its limited zero-sequence impedance. This design flaw, combined with incomplete testing and design reviews, led to significant anomalies in the system's response during earth faults.

The analysis of disturbance recorders highlighted several key issues, including earth currents exceeding expected values, phase imbalances, and waveform distortions. These anomalies were traced back to core saturation effects, which were further confirmed through simulations and harmonic analysis.

To address these issues, it is essential to implement thorough design assessments and testing protocols. Verifying the core configuration and zero-sequence impedance at the factory, along with conducting full voltage tests on earthing transformers, can prevent similar problems in future installations. These measures will ensure that transformers are appropriately designed for earthing applications, thereby enhancing system reliability and safety.

In summary, the lessons learned from this investigation underscore the importance of rigorous design and testing processes in maintaining the integrity of offshore electrical installations. By addressing the identified flaws and implementing the recommended solutions, we can significantly improve the safety and reliability of these critical systems.

V. REFERENCES

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II. VITA

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He earned his master's degree with honors in electrical engineering in 2010 from the University of Rome "La Sapienza." In 2010, he joined Technip Italy as an Electrical Engineer, moved to Kinetics Technology (Maire Tecnimont Group) in 2018 as an Electrical Project Lead, and subsequently joined SBM Offshore in 2019 as an Asset Integrity Electrical Engineer in the Operations Department. During his tenure at SBM, he served as the EC&I Group Lead in Operations and Digital Solution Lead.

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