A Case History of Shore Power Transformer Taps Arcing during No-Load Condition

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Abstract: **The on-board generators of ships use low-grade fuel for power generation. The process of switching off the on-board generators of berthing ships and connecting berthing ships to shore power is called shore-to-ship power supplies (STSPS). This STSPS operation ships minimizes air pollution. To comply with mandatory air-pollution requirements, in 2014, Port of Oakland installed STSPS projects at various berths. In 2015, at Berth 37, a 7.5 MVA, cast-coil transformer within an outside weatherproof enclosure experienced arcing of no-load primary tap connections at 12.47 kV. Installation and testing of all STSPS, including Berth 37, complied with NETA and IEC/IEEE Std 80005-1. At Berth 37, a very sensitive current protection relay scheme cleared the taps arcing ground fault by tipping a 12.47 kV breaker. Arcing occurred when the transformer was energized without any load. No signs of transient overvoltage were observed on the power supply system during transformer taps arcing. Transformer design was per the industry standards. This paper describes the case history of transformer taps arcing and provides recommendations to avoid such incidents, which may cause damage if the arcing ground fault was not cleared quickly by the sensitive protection relay.**

Index Terms**: shore-ship power supplies, shore power, cold ironing, cast-coil transformer, arcing ground fault, sensitive ground fault relay, air pollution, low-resistance grounding, high-resistance grounding.**

I. INTRODUCTION

Major ports around the world today are implementing STSPS projects to comply with IEC/IEEE Std 80005-1 [1]. They are also called shore power projects, cold ironing projects, or Alternative Maritime Power (AMP) projects to minimize air pollution by turning off the on-board generators of berthing ships at ports. In 2014, to comply with California air pollution control requirements, Port of Oakland (Port) installed such STSPS projects at numerous berths to maintain ships' connection to shore power to keep maritime business in operation at the Port. A brief description of the STSPS is provided for those who may not be familiar with such projects.

This paper describes a case history of no-load primary taps arcing of a 7.5 MVA, 12.47 kV – 6.6Y/3.81 kV transformer. Underground 12.47 kV duct-banks with proper electric vaults brought power from the Port main substation to Berth 37. The main substation consisted of 115 kV dual transmission lines connected to two utility-owned power transformers with wye connected 12.47 kV solidly grounded secondary. Two separate 12.47 kV metal-clad switchgears at the main substation provides radial power supply to the entire Port's infrastructure, including Berth 37.

No evidence of internal and external transient overvoltage was observed on the power supply system. It is possible that the utility power system may have +3% above the nominal supply voltage of 12.47 kV, which is generally the normal utility voltage regulation of +/- 3%. The transformer was without any load during arcing. Transformer specifications with outdoor National Electrical Manufacturers Association (NEMA) 3R enclosure included space heaters and louvers, and clearances from taps to enclosure metallic structure were per the industry standards. The transformer was manufactured and tested per standards [3] [5] [6]. The enclosure was equipped with drip-proof louvers and had thermostatically controlled temperature space heaters. It was noted that such arcing occurred two times during rainy and windy weather, and the transformer was without any load but was under energized conditions for both incidents.

The manufacturer of the transformer provided seven (7) similar transformers with enclosures of the same design and was requested to determine the cause of taps arcing and evaluate the extent of damage to the transformer. After a thorough investigation and assessment by the transformer manufacturer, the manufacturer then provided the necessary repair to the transformer, which involved cleaning and re-insulating all the components involved in the arcing fault. The repair was followed by thorough inspection and testing. Tests included: a) insulation resistance tests, b) turns ratio tests, and c) insulation power factor tests, all in accordance with InterNational Electrical Testing Association (NETA) Standard for Acceptance Testing Specifications. The tests confirmed that there was no internal damage to the transformer, and it is evident that there was no transient surge that may have caused any internal resonance due to inherent winding inductance and capacitance parameters. Additionally, Chevron louvers were installed to improve the weatherproofing of the transformer enclosure. As a result, the Port facilities staff energized the transformer without any arcing problem so far. A description of no-load primary taps arcing of a 7.5 MVA, 12.47 kV – 6.6Y/3.81 kV transformer is included in this paper. This paper ends with references and provides recommendations to avoid such incidents.

A major application concern is that similar installations exist at other ports around the world, and it is a common and logical practice to keep STSPS substation transformers energized

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between the cold ironing intervals to avoid turning transformers on and off for each cold ironing operation. This is time consuming and adds magnetic stress to the transformer windings. The stored flux in the transformer steel core may not become zero at the time it is reenergized again after deenergizing when the previous cold ironing operation was completed. Such no-load taps arcing should be avoided by improving transformer taps design by implementing recommendations included in this paper.

II. DESCRIPTION OF A COLD IRONING PROJECT

This paper starts with a brief description of a typical STSPS project. STSPS involve special unique power distribution equipment, including a medium-voltage (MV) very heavy power receptacle inside an underground vault near the ship berthing wharf. It also requires the connection of an underground vault power receptacle to a matching power plug attached to the end of an MV cable rolled down by the cable management system (located at the ship), which is connected to a power receptacle for flow of shore power to the berthing ship when the ship's on-board generators are turned off [2]. Only one ship can be connected to one cold ironing transformer at one time [1]. Once the cold ironing operation is over, the cold ironing transformer is left energized without any load, especially when the cold ironing operation at the installed berth is frequent. It is logical to keep the transformer energized rather than switching it off and on for each cold ironing operation.

At the Port, a total of 11 berths were equipped with cold ironing infrastructure. A brief description and special design features of no-load primary taps on a 7.5 MVA, 12.47 kV – 6.6Y/3.81 kV cold ironing cast-coil transformer are included in this paper. The transformer was energized without any load and no transient overvoltage activity was observed during arcing. Sensitive ground fault relay tripped the 12.47 kV power circuit breaker at the time of transformer taps and associated tap connections arcing to ground. This incident leads to a logical and practical conclusion that the transformer no-load tap connections design should consider installing removable insulating boots and caps. Another design improvement appears to be that all grounded structural members near the no-load tap connections should have a larger clearance than recommended in NEMA based on line-neutral voltage, which is 7.2 kV in this installation. Dielectric air strength in the case of ports near the wharf area decreases with moisture and salt particles in the atmosphere. How, in general, an arcing ground fault in a three-phase power supply system takes place is included in [7][8], which then can be applied to a cold ironing project as discussed in this paper.

III. TRANSFOMER NAMEPLATE

The 7.5 MVA cast-coil transformer was installed in an outdoor NEMA 3R enclosure. The transformer primary windings connected in the delta configuration were equipped with no-load taps, two taps each at 2.5% above and four taps each at 2.5% below the set taps voltage of 12.158 kV. Transformer secondary was connected in wye at 6.6Y/3.81 kV with a high-resistance grounded (HRG) neutral resistor rated at 30A for 10 seconds. Transformer nameplates show all primary no-load taps, 1 through 16, with taps set at 1-6 and 2-13, which correspond to a voltage rating of 12.158 kV as seen in Fig.1. A Delta connected primary connection diagram is also seen in Fig. 1.

To protect the transformer from transient overvoltages, properly rated metal-oxide varistors (MOV) surge arresters were installed inside the 12.47 kV metal-enclosed disconnect switch, which is close-coupled to transformer primary [4]. The transformer was installed and tested at the site per the contract requirements. The transformer went through cold ironing operations from Jan. 2014 through Dec. 2015 and there were no signs of any performance issues.

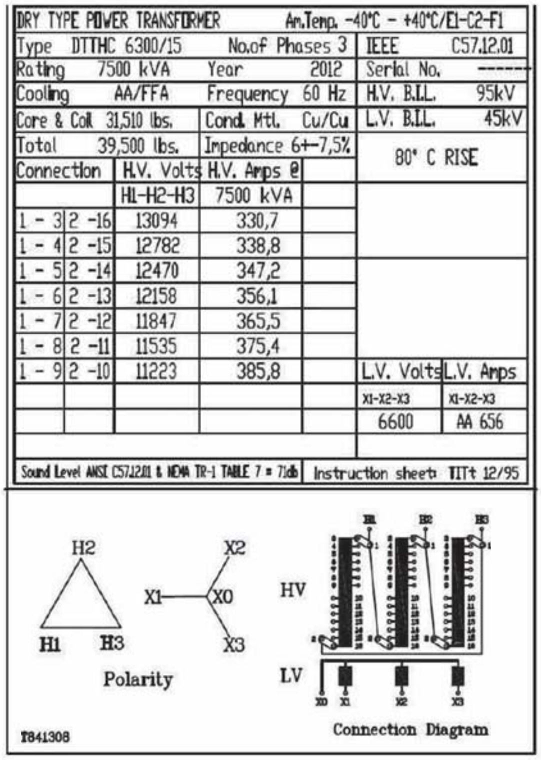

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Fig. 1 Transformer nameplate

IV. PORT POWER SUPPLY SYSTEM

Power is supplied by the Port's main substation, which receives utility power by two independent 115 kV overhead transmission lines intercepting high-voltage outdoor power circuit breakers and two main step-down power transformers with 115 kV to 12.47Y/7.2 kV delta connected primary and Y connected solidly grounded secondary. The solidly grounded power system definition has changed to "effectively grounded system" as defined in AIEE Standard No. 32, 1947 [8]. The 12.47 kV switchgears from two main transformers becomes the Port's power supply system by an underground radial distribution network to each separate berth for different tenants. With some special agreement with the utility, the Port uses its own power metering equipment for each tenant. Not getting into the details of tenant lease agreements used by the Port, the existing underground distribution system and existing electrical infrastructure were upgraded to accommodate cold ironing projects in various berths in 2014. The Berth 37 cold ironing substation discussed in this paper is one of the cold ironing projects installed in 2014. Fig. 2 shows the physical location of Berth 37 and clearly indicates that this site is subject to moist air with ocean gusts containing salt particles. The transformer outdoor NEMA 3R enclosure was specified to consider the site environment conditions. Refer to Fig. 3 for the 12.47 kV metal-clad vacuum circuit breaker fully equipped with phase and ground fault protection relays.

Fig. 2 Berth 37 Cold Ironing substation physical location

V. SUBSTATION ONE LINE DIAGRAM

The Berth 37 cold ironing substation power supply one-line diagram is shown in Fig. 3 where the 12.47 kV power supply comes from Port's main substation by underground duct banks. Two red circles in Fig. 3 represent the power circuit breaker and transformer, respectively.

VI. CAUSE OF TAPS ARCING TO GROUND

It is known that the dielectric strength of the air decreases with dampness and is affected by air pressure, conductive dust and salt particles, and other coastal weather contaminations. Transformer enclosures are subject to infiltration caused by direct and indirect prevailing winds coming over the ocean/bay water. Such winds can change direction and can penetrate through enclosure openings thereby directly hitting the transformer taps. This can lead to a damp contaminated condition of tap holes, like the transmission line insulators in the coastal area, which causes insulator flashover. The damp contaminated condition is the most common cause of flashover because most contaminants are electrically conductive when damp or wet [8].

The most probable cause of transformer taps arcing during wet weather conditions can be correlated to the conductive layer of contaminants over the uninsulated tap holes. Manufacturers of transformers for such coastal locations should review this case history of taps arcing to avoid such occurrences by a) providing removable insulating boots and caps to fit over the tap-connections, b) increasing distance from taps to grounded enclosure members, or c) a combination of both a) and b).

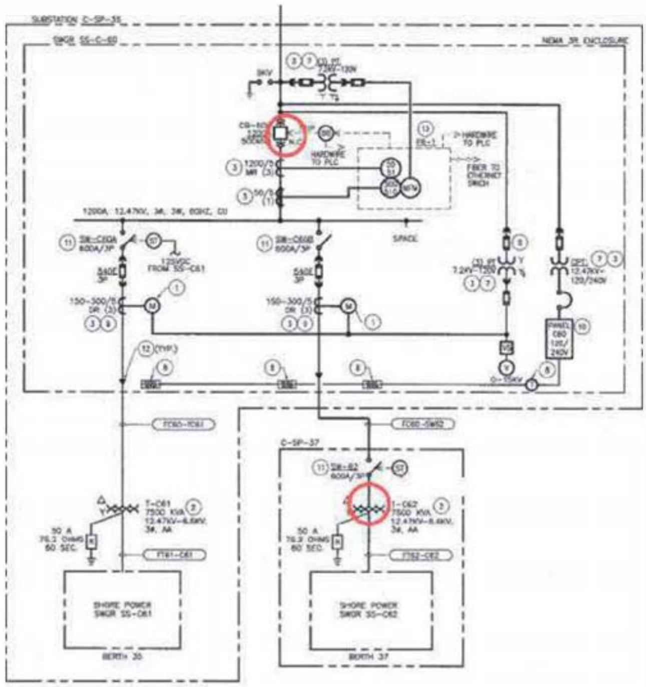

Fig. 3 Berth 37 substation One-line Diagram

VII. SUBSTATION LAYOUT AND ENCLOSURE

This section includes Fig. 4, which shows substation layout with bollards to protect the enclosure from vehicle traffic. Fig. 5 shows the transformer outdoor enclosure with louvers where on one side there is a close-coupled no-load disconnect switch and on the other side a transformer secondary neutral grounding resistor. These photos are very important in understanding that coastal weather and wind can enter the enclosure and hamper the insulation integrity of the air dielectric. The transformer taps, tap bushings, and grounded metallic support inside the enclosure can then cause phase-to-ground arcing during bad weather conditions.

Fig. 4 Berth 37 substation layout photo

Fig. 5 Substation transformer outdoor enclosure

VIII. SNAPSHOT OF EVENTS – PROTECTION

Table I shows a snapshot of events recorded during arcing and both phase and residual ground protection relays. It shows that the fault occurred on 12/13/2015 and lasted for 0.1667 seconds (10 cycles) 08:35:39.707021 to 08:35:39.873721 and that the circuit breaker was tripped by the ground fault current relay as the ground fault current magnitude far exceeded the pickup settings of the ground fault current relay.

Table I: Snapshot of events recorded during transformer tap arcing

312	Dec 13 2015 08:35:39.873721	PHASE TOC1 DPO B
311	Dec 13 2015 08:35:39.873721	PHASE TOC1 DPO A
310	Dec 13 2015 08:35:39.873721	NEUTRAL TOC1 DPO
309	Dec 13 2015 08:35:39.798708	Cont Op 3 On
308	Dec 13 2015 08:35:39.798708	Virt Op 1 On
307	Dec 13 2015 08:35:39.798708	NEUTRAL TOC1 OP
306	Dec 13 2015 08:35:39.732025	NEUTRAL TOC1 PKP
305	Dec 13 2015 08:35:39.707021	PHASE TOC1 PKP B
304	Dec 13 2015 08:35:39.707021	PHASE TOC1 PKP A

PARAMETER	CT F1
Phase CT Primary	600 A
Phase CT Secondary	5 A
Ground CT Primary	600 A
Ground CT Secondary	5 A

As stated earlier, the IEEE very inverse relay settings of the neutral time overcurrent (TOC1) shown above and its operation noted under line 307 in Table I caused tripping of the power circuit breaker to clear the arcing ground fault.

Table II: Protection relays settings

PARAMETER	NEUTRAL TOC1
Function	Enabled
Source	SRC 1 (SRC 1)
Input	Phasor
Pickup	0.500 pu
Curve	IEEE Very Inv
TD Multiplier	0.09
Reset	Instantaneous
Block	OFF
Target	Latched
Events	Enabled

PARAMETER	PHASE TOC1
Function	Enabled
Signal Source	SRC 1 (SRC 1)
Input	Phasor
Pickup	1.000 pu
Curve	IEEE Very Inv
TD Multiplier	1.00
Reset	Instantaneous
Voltage Restraint	Disabled
Block A	OFF
Block B	OFF
Block C	OFF
Target	Latched
Events	Enabled

Fig. 6, Graph 1 indicates very high fault currents on phase A (FI-1A) and phase B (FI-1B), whereas the very small current in phase C (FI-1C) and the vector sum of these three unbalanced currents resulted in a very high ground fault current (F4-1G). Graph 2 in Fig. 6 indicates close to nominal line-neutral voltage (F7-VC) on phase C and much reduced voltages of phase A (F5-VA) and phase B (F6-VB).

CHANNEL		GRAPH	MAGNITUDE / ANGLE
F1-IA		Graph 1	5.753 kA -8.57°
F2-IB		Graph 1	5.240 kA -172.49°
F3-IC		Graph 1	2.75 A -248.95°
F4-IG		Graph 1	1.612 kA -252.26°
F5-VA		Graph 2	2.782 kV 0.00°
F6-VB		Graph 2	2.098 kV -36.50°
F7-VC		Graph 2	7.579 kV -192.16°
F8-VN		Graph 2	11.06 V -327.17°

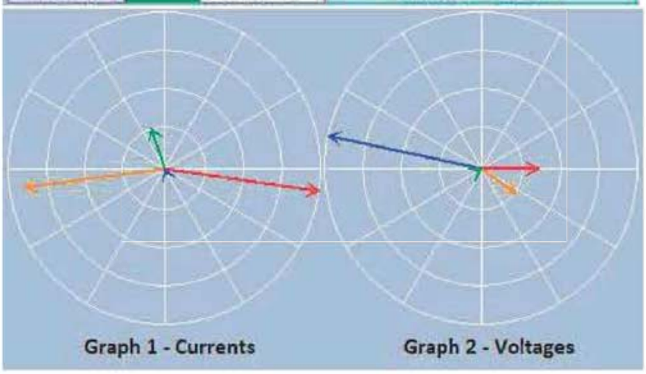

Fig. 6 Current and voltage phasor diagram during arcing fault

This concludes that there was an arcing ground fault from transformer delta that connected winding H2 (phase B) and H3 (phase C) to ground. Fig. 7 shows 60Hz currents and voltages before, during, and after the fault.

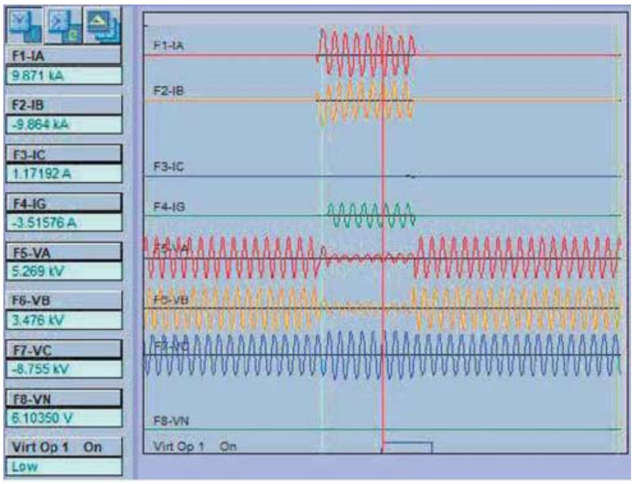

Fig. 7 Currents and voltages snapshot of the fault

IX. EVIDENCE OF TAPS ARCING

To determine the cause of breaker tripping, the transformer enclosure was opened for inspection. Signs of arcing were observed on the taps, tap connectors, and outer surface in the middle of phase B coil and the bottom of phase C coil as shown in Fig. 8. A few of the voltage tap-connection bolts and bolt holes were melted as a result of arcing fault. The arrangement of taps and tap connections for delta primary voltage may vary from the manufacturer of the transformer depending upon the winding construction. However, Fig. 8 and Fig. 9 show actual configuration of taps and tap connections for this paper.

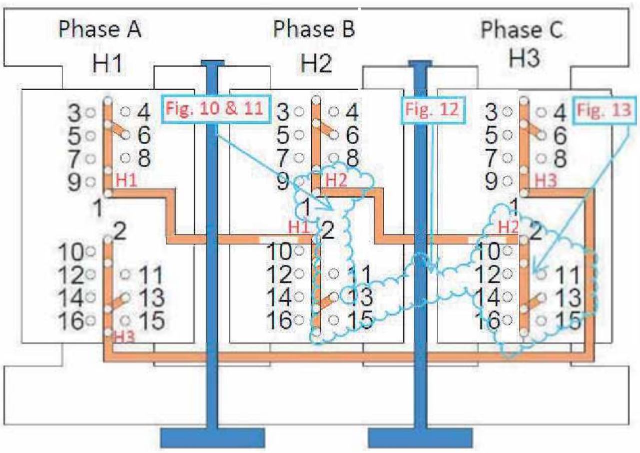

Fig. 8 Signs of arcing on overview of the all three windings layout drawing

Locations of taps for the arcing of phases A and B are shown in Figures 10, 11, 12, and 13. The grounded support member between the coils for phases B and C, (shown in blue color in Fig. 9) was eventually breached over by the arcing on phases A and B taps connections located on the surfaces of phase B and C coils. Again, as stated earlier, it can be seen from Fig. 8 and Table I line 307 that tripping of the circuit breaker occurred by the ground fault relay.

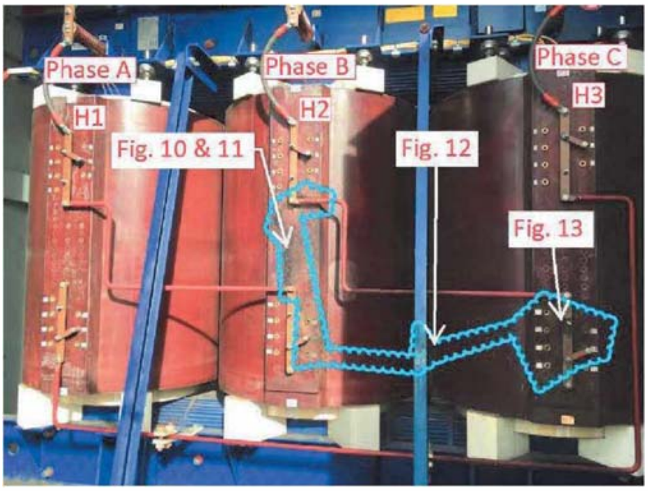

Fig. 9 Areas showing signs of arcing on phases B and C

Fig. 10 Tap 10 and connector 2 on middle leg (phase B) arcing signs

Fig. 11 Connector 1 to connector 2 on middle leg (phase B) arcing signs

Fig. 12 Signs of melting below grounded support member on phase B

Fig. 13 Taps 10 and 12 and outer surface show signs of arc fault

X. WEATHER REPORT DURING ARCING

The weather reported during tap arcing included rain and a storm. The evidence of arcing showed rainwater intrusion through the ventilation louvers. The dirt that collected inside the transformer and the water intrusion created a tracking path for arcing current, which tripped the breaker by protection relays. The evidence of rain is seen in Fig. 14, which is a photograph taken from the flooded freeway (courtesy of local newspaper).

Fig. 14 Flooded freeway – rain during transformer taps arcing

What would have been the effect on transformer tap arcing discussed in this paper if the existing effectively grounded 12.47 kV power system were converted to low-resistance grounded (LRG) power system by installing 1200 A, 10 Sec. neutral resistor at each of the main transformer. See Chapter 19 I.3 page 646 [8] for an effectively grounded power, which is currently existing at the Port and is called solidly grounded power system.

As the power systems ages, such solidly grounded power systems lead to excessive line to ground fault currents which no doubt are cleared by sensitive ground fault protection relays, but it is unclear whether such faults cause insulation weakness at some locations which may lead to major damage in the next fault condition.

Authors would present a future paper and discuss how fault energy is reduced to 1% when ground fault current is reduced to 1200 by LRG when a solidly grounded power system ground fault current is 12 kA. This reduced energy reduces fault hazard to enhance safety. All modern ground fault protection relays are sensitive and retrofitting solidly (effectively) medium-voltage older power systems at Port facilities to LRG system can reduce fault hazards and enhance safety without losing protection by LRG systems.

XI. CONCLUSIONS AND RECOMMENDATIONS

1) The typical outdoor transformer enclosure has an issue with avoiding rainy or dusty wind hitting the transformer tap locations causing arcing, especially when louver design is not suitable for the site environment. An alternative to enclosure design improvements is installing removable insulating boots and caps on tap-connections, making greater clearances from grounded metallic support members, and installing water/dust proof filters behind louvers.

2) The manufacturers of cold ironing power substation transformer enclosures must provide removable insulating boots and caps to cover the tap connections and unused tap connection holes to ensure adequate dielectric air strength is maintained during wet weather conditions.

3) If arcing of taps were to occur during cold ironing operation, then cold ironing operation could be interrupted and cause delays and create possible safety hazards to operations staff handling shoreside operation.

4) The fault was cleared to avoid major damage which otherwise could have damaged transformer internal windings.

5) It is recommended that the working group members of IEC/IEEE Std 80005-1: 2019 review this tap arcing problem for possible revision to the standard.

ACKNOWLEDGEMENT

Authors would like to acknowledge the Port of Oakland for sharing the case history with the marine industry to help avoid similar incidents at other ports by improving transformer enclosure and tap connections design.

REFERENCES

[1] IEC/IEEE Std. 80005-1: June 2019: Utility connections in port-Part 1: high voltage shore connections (HVSC) systems- General Requirements.

[2] Dev Paul, Kevin Peterson, and Ben Chavdarian, "Designing Cold Ironing Power Systems," IEEE Industry Applications Magazine, Vol. 20, no. 3, Issue 5, May/June 2014.

[3] IEEE Std C57.12.00-1989, Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin Encapsulated Windings.

[4] Dev Paul and Vahik Haddadian, Transient Overvoltage Protection of Shore-to-Ship Power Supplies, "IEEE Transactions on Industry Applications."

[5] IEEE Std 57.12.01, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid and /or Resin-Encapsulated Windings

[6] IEEE Std 57.124-1991, Recommended Practice for the Detection of Partial Discharges and Measurement of Apparatus Charge in Dry Type Transformers.

[7] J.R. Dunki-Jacobs, F.J. Shields with Conrad St. Pierre, Industrial power System Grounding Design Handbook

[8] Electrical Transmission and Distribution Reference Book by Central Station Engineers of the Westinghouse Electric Corporation, Fourth Edition, Fifth Printing, Copyright 1964.

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