# TRANSFORMER SYMPATHETIC INRUSH EFFECT ON RADIALLY FED OFF-SHORE OIL PRODUCTION PLATFORMS: A CASE STUDY


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***Abstract*** – Electrified oil platforms are becoming predominant in the oil and gas industry for offshore production. Large transformers and long submarine cables are being utilized to ultimately supply power to electrical submersible pumps (ESPs). Consequently, detailed analysis is required to study complex phenomena, including switching transients associated with transformer and cable energization. This paper presents a case study for the impact of transformer energization on system voltage for radially fed power network. In the case where multiple transformers share the same primary bus, the switching transients associated with one transformer energization causes a voltage sag affecting the loads connected to the other adjacent transformers. The sag is attributed to a sympathetic inrush phenomenon experienced by the moderately loaded transformers sharing the primary bus with the transformer being energized. The authors conducted field measurements using power quality recorders, and built a power system model to reproduce the field results using commercially available transient modeling software. Remedial solutions were studied to alleviate the impact of transformer energization on system voltage.

*Index Terms* — Offshore platform, submersible pumps, switching transients, sympathetic inrush, transformer energization, and voltage sag.

## I. INTRODUCTION

Power quality has gained attention from power system operators due to the adverse impacts potential disturbances can have on service continuity, especially with the increasing utilization of sensitive loads. With advancements in oil and gas production technologies, more sophisticated electrical equipment is being utilized to satisfy process requirements. For example, electrical submersible pumps (ESPs) are being used widely in offshore oil platforms, and they are typically driven by adjustable speed drives (ASDs) for speed control. As a power electronic device driven by a controller, ASDs are sensitive to power quality issues (e.g. voltage sags).

A potential power quality issue for offshore oil involves a voltage sag during unloaded energization of power transformers. This issue is studied in this work considering a typical offshore facility as a case study. The facility is considered to be fed by a single 50 km long 115 kV submarine cable that feeds two adjacent 115/13.8 kV transformers through a 115 kV gas insulated switchgear (GIS). As shown in Fig. 1, the two main transformers are feeding a double-ended 13.8 kV switchgear, which feeds multiple offshore production platforms using 13.8 kV submarine cables. The voltage is further stepped-down on the production platforms to 480 V, where the ASDs driving the ESPs are connected.

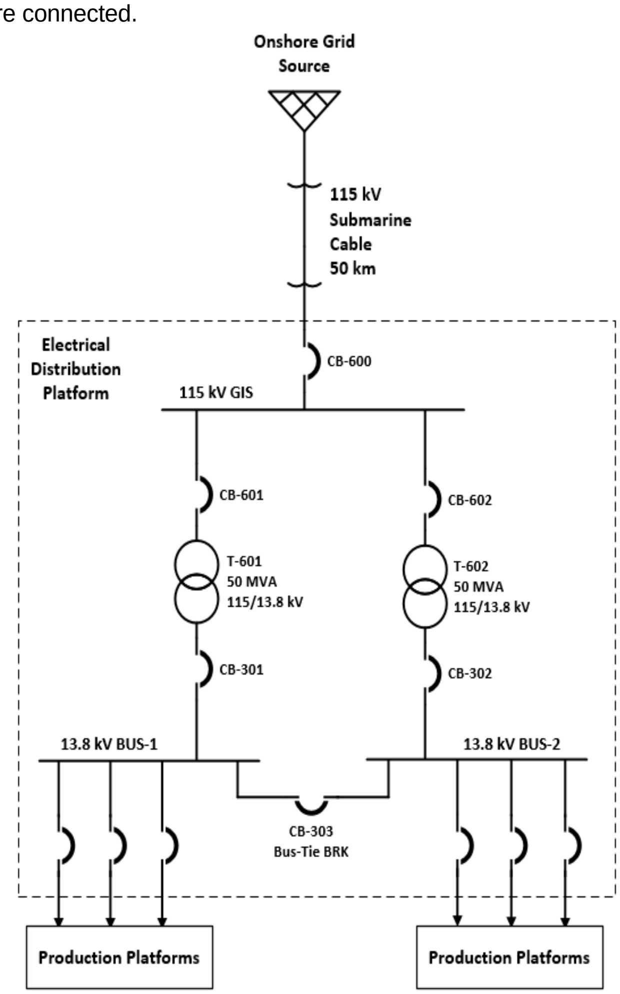


Fig. 1 Offshore Platform Electrical Network

The double-ended 13.8 kV switchgear operates normally with an open tie-breaker where each main transformer feeds the load of one bus section. When one of the main transformers is taken out-of-service, the tie-breaker of the double-ended switchgear is closed, to feed the entire load from one transformer. During the restoration of normal system configuration (open tie-breaker), the restored transformer is energized by closing its primary breaker, while the secondary breaker is kept open.

A simulation model was developed for the power system network of the facility, to study the system behavior under different operating conditions, and assess the remedial solutions offered by industry. The developed model and simulation results are discussed in this paper, which examines the effectiveness of solutions considered for the subject case study. In addition, a sensitivity analysis was carried out to determine the contribution of several design and operational factors for the discussed issue including the sub-transmission system voltage level, system source impedance, transformer saturation characteristics, and system loading.

The rest of the paper is organized as follows: Section II provides information about transformer's inrush and sympathetic interaction phenomenon. Section III describes the developed network model and the simulation results. The sensitivity analysis results are discussed in Section IV. Finally, Section V presents the conclusions of this work.

## II. BACKGROUND

During energization, the transformer draws an inrush current, which is caused by an abrupt change in the magnetizing voltage, as the system voltage is applied to the primary winding [1]. The flux in the transformer core is related to the voltage drop across the winding according to Faraday's Law, thus, at the switching instant there is a discrepancy between the residual flux in the core, and the instantaneous steady-state flux value corresponding to the point on the voltage waveform at which the transformer is switched on.

The discrepancy is maximum when the transformer is energized at the moment corresponding to zero crossing on the voltage waveform. In Fig. 2 [2], the steady-state flux waveform corresponds to the shown voltage waveform during normal transformer operation. The flux swing from a peak in one direction to the peak in the other direction corresponds to the volt-time integral of a half-cycle wave of the voltage between two zero crossings [3].

However, during transformer switching and specifically for the case of zero angle switching, the flux will follow the transient flux curve in Fig. 2 reaching up to twice rated flux ($\phi_m$). Therefore, a large amount of magnetomotive force (mmf) is needed to produce an equivalent flux. The mmf is generated by the winding current, hence a high current (inrush) is absorbed by the transformer, reaching as much as 10 times the transformer full-load current. From the saturation curve (top right graph in Fig.2) peak transient flux corresponds to a very high current as the transformer operates in the saturation region.

Several factors impact the severity of inrush current, the first being instantaneous voltage at the time of switching. As stated, peak inrush corresponds to the voltage waveform zero-crossing; likewise, 90° waveform positions—maximum or minimum instantaneous voltage—result in a minimum inrush scenario. Another factor affecting the transformer inrush is the remnant flux in the transformer's core during energization, which would drive the core further into saturation. Remnant flux is always present in the transformer's core, even when de-energized due to the hysteresis effect associated with ferromagnetic materials [4]. In addition, the severity of inrush current is impacted by source impedance. The higher the system short-circuit (lower source impedance), the less source impedance limits inrush.

One of the major impacts of transformer inrush current is introducing asymmetrical components to the voltages at the source bus. When another operating transformer shares the same primary bus with the energized transformer, it will cause it to draw an inrush current, which will further impact the source voltages [5]. The inrush current drawn by the operating transformer is called sympathetic inrush which is due to a coupling effect that is caused by the asymmetrical voltage drop across the system impedance of the common supply source of the two transformers.

The asymmetrical voltage drop caused by the transformer energization has a DC decaying component that would produce an offset flux in both transformers cores. This offset flux is opposite in polarity to the primary induced flux, hence it will produce a current in the transformer with reversed polarity that would dampen its inrush current. However, as the asymmetrical voltage drop is applied to the other transformer sharing the same source, a flux offset will be produced in the adjacent transformer

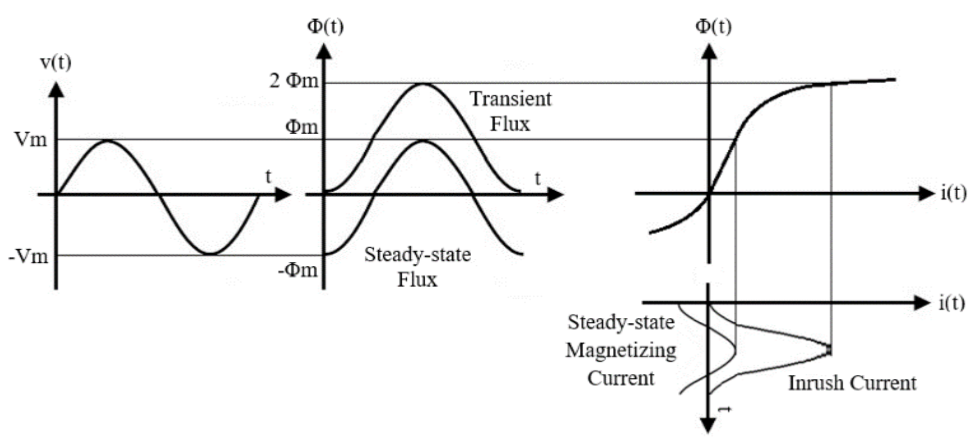


Fig. 2 Transformer's energization curves [2]

core as well producing a sympathetic inrush current that has an opposite polarity to the inrush current of the transformer being energized [6].

The sympathetic interaction between the two transformers and its impact on the common bus voltage intensifies with time hence it results in prolonging the switching transient condition. Contrary to inrush current, sympathetic inrush current is greatest when the system short circuit capability is low—the lower capability is indicative of high source impedance which increases the severity of the voltage offset at the common transformer source bus. The impact of the sympathetic interaction prolongs voltage sag associated with transformer energization, [7] as it extends the duration of the transformer's inrush mode.

The sympathetic inrush phenomenon could potentially impact the operation of offshore facilities with the system configuration shown in Fig.1, since the two main transformers share the same primary bus. The impact would be a prolonged deep voltage sag during transformer energization, a direct result of the sympathetic effect compounded by the weak system source due to a long submarine cable.

## III. NETWORK MODELING AND SIMULATION

A model was developed using a commercially available power system modeling software for the network shown in Fig. 1. The onshore grid source short circuit level was modeled using a 115 kV voltage source with a Thevenin equivalent impedance resulting in a short circuit level of 3110 MVAsc and X/R ratio of 8.7. A widely adopted frequency dependent cable model, Fig. 3, was used to model the 115kV submarine cable using the parameters obtained from the vendor datasheet.

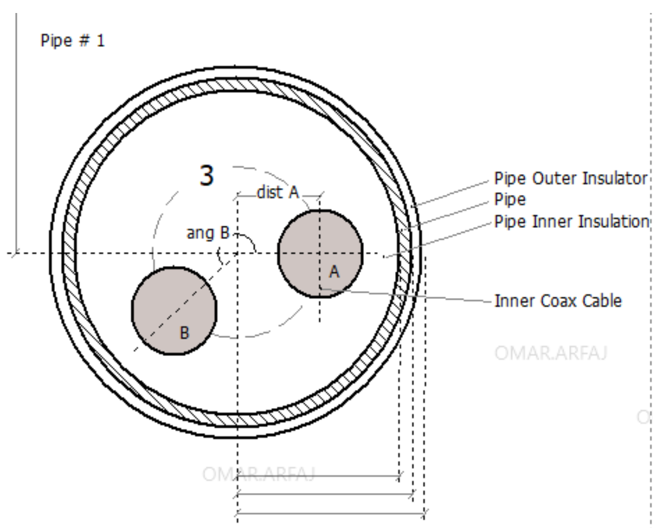


Fig. 3 Submarine cable frequency dependent model

A frequency dependent model, Fig. 4, was used for the main 115/13.8 kV transformers with typical values for stray capacitances. Transformers parameters are obtained from the vendor including leakage reactance, losses, and saturation characteristics (i.e. air core reactance, magnetizing current, and knee voltage). The air core reactance is calculated based on winding geometry and number of turns. The magnetizing current is measured during the no-load test, while the knee voltage is obtained from the saturation curve as it corresponds to the voltage at which a 10% increase in applied voltage results in 50% increase in the magnetizing current. The parameters used for the transformer model are shown in Table I. Dyn1 indicates a delta high-voltage wingding, a wye low-voltage winding with neutral bushing, and a 30° phase shift between windings [8].

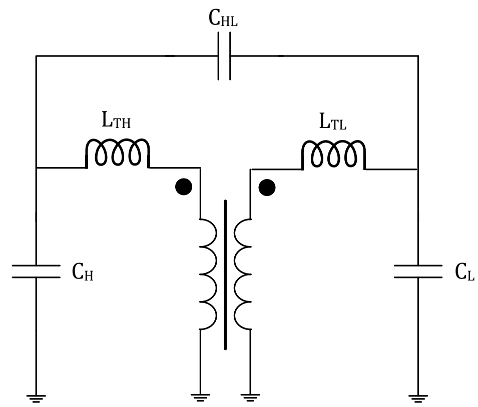


Fig. 4 Transformer model with stray capacitances

TABLE I
13.8kV TRANSFORMER PARAMETERS

| *Parameter* | *Value* |
|---|---|
| Power Rating | 50 MVA |
| Vector Group | Dyn1 |
| Leakage Reactance | 0.09 pu |
| Eddy Current Losses | 0.00077 pu |
| Copper Losses | 0.0023 pu |
| Air Core Reactance | 0.18 pu |
| Magnetizing Current | 0.18% |
| Knee Voltage | 1.10 pu |

The 13.8 kV submarine cables and the 13.8/0.48 kV transformers are modeled using vendor datasheet data and typical values for missing parameters, while each production platform load is modeled as lumped constant power load since it mainly consists of motors. The off-load tap changers of the 13.8/0.48 kV transformers are fixed at actual operating tap position.

The model could not be validated against actual system performance due to the unavailability of real-time measurement data. As such, a philosophy similar to studies conducted for new systems was adopted, in which developed model is assumed sufficient to approximate system behavior during transformer switching action.

The base case was simulated considering a gang-operated GIS circuit breaker for transformer energization representing the current system configuration. In addition, a 0.8 p.u. remnant flux was considered for the energized transformer with an assumed voltage zero crossing—the worst-case scenario. In the simulation results, minimum starting voltages are referenced instead of voltage drop (ΔV) since ASD's manufacturers have confirmed that when the applied voltage reaches below 0.9 p.u. for more than 0.2 seconds, the ASD's ride-through capability would be exceeded resulting in an overcurrent trip.

The simulation results for the base case in Fig. 5 show a large voltage drop resulting in less than 0.9 p.u. for one of the line voltages at the 480 V equipment lasting for around one second. The duration of the voltage sag below 0.9 p.u. exceeds the ASD's ride-through capability as confirmed by the manufacturer, thus tripping of multiple units. These trips would actually result in speeding up the voltage recovery which was not considered in the simulated case study.

The inrush current associated with the base case reached up to 5.9 p.u. for the transformer under energization as shown in Fig. 6, while the other parallel transformer experienced a sympathetic inrush current reaching up to 1.9 p.u. of its rated current (Fig. 7). Two practical solutions were considered to address the sympathetic interaction. The first solution is de-magnetizing the transformer prior to energization. The second solution implementing point-on-wave switching for the GIS circuit breaker at the primary side of the transformer.

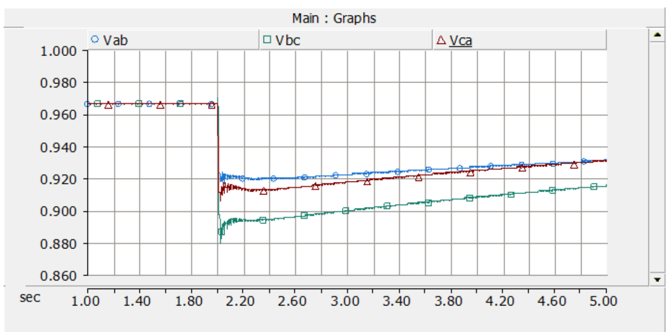


Fig. 5 Voltage profile for base case study

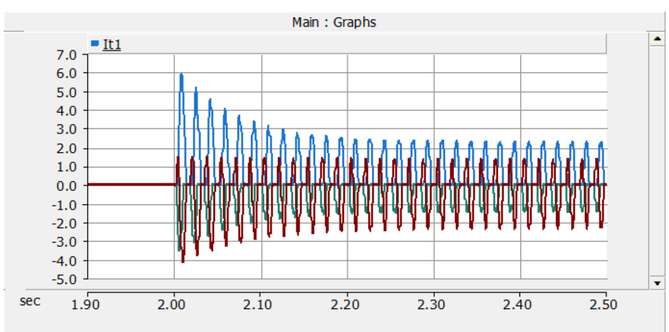


Fig. 6 Transformer energization inrush for base case study

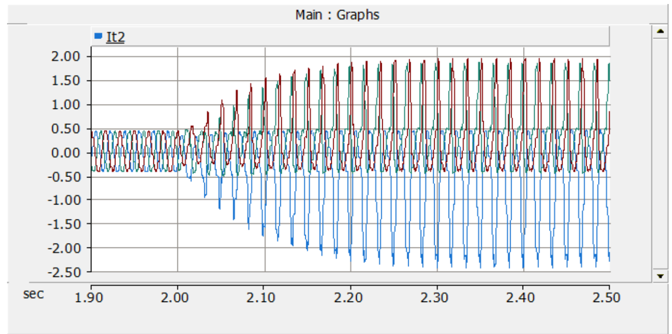


Fig. 7 Transformer sympathetic inrush for base case study

*Transformer De-magnetization*

As previously stated, remnant flux in the transformer core will increase the transformer inrush and consequently it will increase sympathetic interaction. Therefore, a zero-remnant flux case was simulated assuming that the transformer was demagnetized prior to energization. Transformer de-magnetization is achieved through primary current injection with waveforms to stimulate the hysteresis characteristic of the transformer's core until a zero-flux point is achieved. The applied waveform could be a decreasing AC voltage or a decreasing DC voltage with alternating polarity [9].

The simulated case for a zero remnant flux transformer showed reduction in voltage drop as a result of transformer energization as shown in Fig. 8. The voltage sagged below 0.9 p.u. for only a few cycles which is within the ride-through capability of the ASDs. Hence it is expected that applying the de-magnetization solution would reduce the impact of transformer energization on the system voltage.

De-magnetization of a transformer of large size is possible using de-magnetization features of advanced transformer testing devices as confirmed by vendors. However, it might be impractical to perform the de-magnetization before every energization as it involves accessing transformer terminals which could be a tedious task depending on the transformer configuration

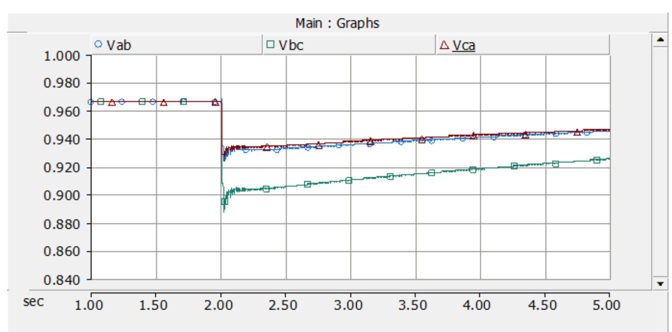


Fig. 8 Voltage profile for transformer de-magnetization solution case study

*Point-on-wave Switching*

Point-on-wave switching scheme is a mature technology utilized for different applications including shunt capacitors, shunt inductors, and power transformers switching. In point-on-wave switching schemes, the poles of the three phases are closed at the point corresponding to the peak voltage point-on-wave of the respective phase. Implementing this switching scheme requires modifying the 115 kV GIS circuit breakers from a gang-operated mechanism to independent pole mechanism. This modification allows for control of the switching timing such that each pole closure coincides with the peak point on the voltage waveform of the respective phase voltage. This switching strategy minimizes the inrush current of the energized transformer and as a consequence the sympathetic interaction is also reduced.

This switching scheme was simulated by modeling the high-voltage circuit breaker as three single-pole breakers with proper timing of each pole closure. The scheme is executed by closing phase A breaker after quarter of a cycle from its voltage zero crossing moment. Then closing phase B and C breakers in sequence with a timing of one-third of a cycle between the three phases. Two cases were considered; the first case with remnant flux in the transformer core, and the second case with no remnant flux. The first case resulted in maintaining the voltage above 0.94 p.u. while voltage was maintained above 0.96 p.u. in the second case as shown in Fig. 9 and Fig. 10, respectively.

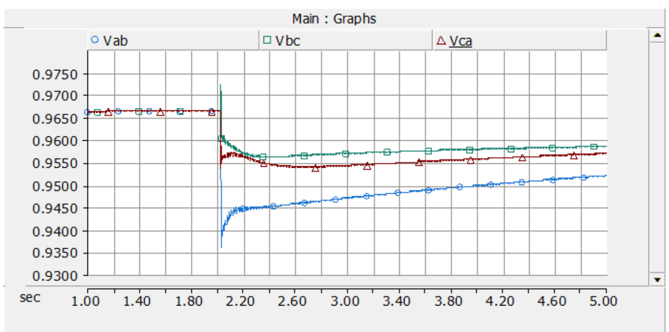


Fig. 9 Voltage profile for the point-on-wave switching with remnant flux case study

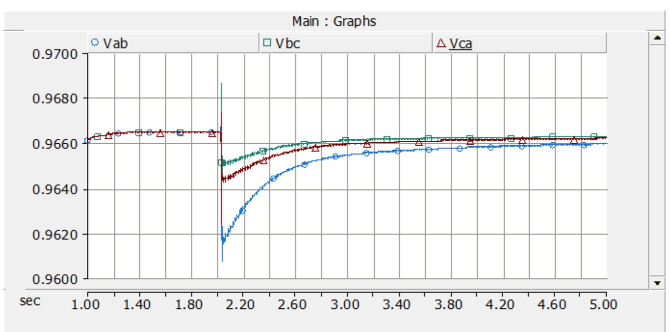


Fig. 10 Voltage profile for point-on-wave switching with no remnant flux case study

## IV. SENSITIVITY ANALYSIS

The configuration shown in Fig. 1 is a typical configuration for these types of offshore oil facilities, and it may be utilized again at future sites. Therefore, it is useful to identify the impact of design factors on the severity of the sympathetic interaction that exists between the transformers sharing the same primary bus. Several design factors are studied in this work; sub-transmission system voltage level, system source impedance, transformer saturation characteristics, and system loading.

*System Voltage*

Several factors affect the selection of sub-transmission system voltage for offshore facilities including; available voltage levels at nearest onshore bulk substations, the size of offshore facility load, and the distance and route of interconnecting submarine cable. Three standard voltage levels are considered in the present analysis; 69 kV, 115 kV, and 230 kV.

The system short circuit impedance was maintained at the same level for the three cases while adjusting the transformer's primary voltage and associated impedance based on typical standard values. The resultant per unit voltage drop at the 480 V level as a result of energizing the primary transformer assuming the base case configuration is shown in Fig. 11. Results show that system voltage level has a significant impact on the severity of voltage drop caused by sympathetic interactions, the higher the system receiving voltage level the lower the impact of transformer energization on utilization voltage.

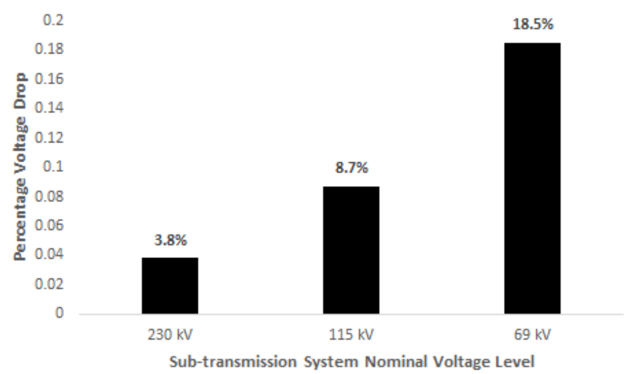


Fig. 11 Percentage voltage drops due to transformer energization under different system voltages

*System Source Impedance*

Depending on the robustness of the onshore power supply, the source impedance of the electrical network supplying the offshore facilities varies between minimum and maximum values. This variation is modeled by varying available short circuit level at the source end based on actual site data which shows a variation between 2350 MVAsc and 7970 MVAsc. As reported in [3], the higher the short circuit level the lower the sympathetic interaction between the main transformers, hence lower impact of on system voltage as a result of transformer energization. Resultant voltage drop for the range of available short circuit levels is shown in Fig. 12.

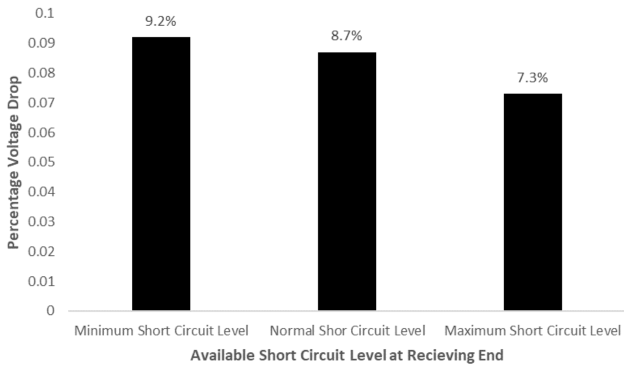


Fig. 12 Percentage voltage drops due to transformer energization under different system short circuit level

*System Loading*

In the double-ended switchgear configuration shown in Fig.1, when one main transformer is taken out-of-service for maintenance the entire facility load is supplied through the second main transformer. After completion of maintenance activities, the system is normalized by returning the transformer back to service. This entire process is executed while the offshore facility maintains normal production. However, system loading varies over time, hence the loading at the moment of energization is not fixed.

The transformer energization is simulated under different system loading conditions; minimum, normal, and maximum. The lighter the system loading, the higher the voltage drop as shown in Fig. 13. The impact of system loading considered to be insignificant relative to the other factors.

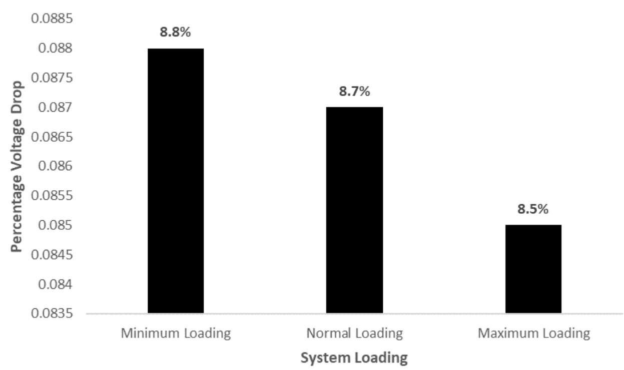


Fig. 13 Percentage voltage drops due to transformer energization under different system loading conditions

*Transformer's Air-core Reactance*

Transformer air-core reactance is an important parameter that defines the saturation characteristics of the transformer. It also impacts the severity of the transformer's inrush since inrush is a direct result of core saturation. The air-core reactance is dependent on the geometry of the exciting winding, which is designed by the manufacturer. The impact of this parameter on the transformer's inrush is analyzed by simulating transformer energization while varying the air-core reactance between 0.18 and 0.26 p.u. in a step of 0.02 p.u. Fig. 14 shows the impact of varying air-core reactance on transformer inrush, sympathetic inrush, and voltage drop. The peak inrush current of the energized transformer decreases as the transformer air-core reactance increases. As such, associated sympathetic inrush and voltage drop also trend down with increasing air-core reactance.

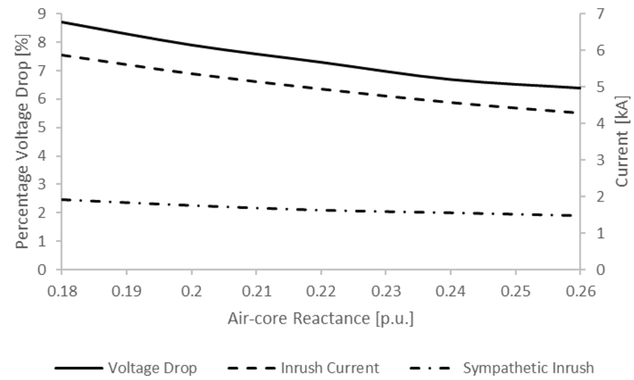


Fig. 14 Percentage voltage drop, inrush, and sympathetic inrush currents due to transformer energization vs. transformer's air-core reactance value

## V. CONCLUSION

Typical offshore network topology for these applications consists of two main transformers sharing the same primary bus that is radially fed by a single submarine cable source. The topology subjects the transformers to sympathetic interactions when energizing one transformer while the second transformer is operational. This phenomenon was studied in this paper and means of mitigating this potential power quality issue were also explored.

The analysis shows that the severity of the voltage sag associated with transformer energization is determined by the magnitude of the transformer inrush which is influenced by multiple factors including; switching angle, remnant flux, and system impedance. Therefore, the voltage sag issue can be mitigated by addressing these factors. Two practical solutions were discussed, point-on-wave switching and transformer de-magnetization. Both solutions have potential to reduce voltage sag to an acceptable level. Point-on-wave switching is more effective in reducing transformer inrush; however, it requires modification of the primary side GIS circuit breaker operating mechanism. Implementation of proposed solutions is currently in process to enhance power quality at the offshore facilities.

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## VII. VITAE

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Hossam Aldossary is an Electrical Engineer with Saudi Aramco in the Consulting Services Department. He graduated with a bachelor degree from the University of Colorado at Boulder in 2015, with focus on control systems, power electronics and electrical machines. Hossam is a member in Saudi Aramco’s specialized UPS, DC Systems and Power Electronics team. Field experience include engineering support to large islanded power systems, UPS, ASD and DC systems commissioning, and power plant construction and commissioning.

Hajhouj Al-Shammari is an Electrical Engineer with Saudi Aramco, Consulting Services Department. He joined Saudi Aramco in 2000 as an electrical engineer providing support and consultancy in the area of power system design, studies, and protection. In 2010, Hajhouj Joined the Project Management team of Yanbu Aramco Sinopec Refinery (YASREF) as lead electrical engineer responsible about the design, equipment selection, pre-commissioning, and commissioning activities of the Hydrocracker plant. Between November 2013 until January 2016, he was the group leader of Electrical Engineering Operations Support unit and then Electrical Engineering Project Support unit within Consulting Services Department. Currently, he is the group leader for Power Systems Design & Automation unit. Hajhouj received his BSc. in Electrical Engineering from King Fahd University of Petroleum and Minerals (KFUPM) and his MSc. in Electrical Engineering from New Mexico State University (NMSU), New Mexico, USA, in 2007.