# Simulation and Analysis of Voltage Sag During Transformer Energization on an Offshore Platform

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# SIMULATION AND ANALYSIS OF VOLTAGE SAG DURING TRANSFORMER ENERGIZATION ON AN OFFSHORE PLATFORM

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***Abstract***—Typically, in offshore platforms, small reciprocating engine generators supply essential loads. At times, it may be necessary to energize a large transformer from these generators. Transformer energization draws high magnetizing current from the generators for several seconds and can have an adverse effect on the system voltage. This paper describes the voltage sag analysis of the energization of two transformers (1.5 MVA and 3.75 MVA) from a diesel engine generator rated at 625 kVA/0.48 kV/0.8 power factor and several gas engine generators rated at 938 kVA/0.48 kV/ 0.8 power factor using real-time dynamic simulations. The power system model of the offshore platform comprises six generators along with an excitation and governor control, two sequentially energized transformers, buses, breakers, and cables. The paper details simulation results for different energization scenarios. The simulations varied the number of generators online, the load on the system, the voltage reference set points, and the transformer parameters. Several factors that influence inrush currents and the resulting voltage sag (such as transformer air-core reactance, breaker closing instant, subsea cable capacitance, and source impedance) were considered. The results of this study aided in designing transformers and developing operational procedures and protection set points.

*Index Terms*—Transformer, inrush, excitation, simulation.

## I. INTRODUCTION

The study of transformer magnetization inrush phenomena has spanned many decades. When system voltage is applied to a transformer that was previously de-energized, a transient current as high as ten times the rated current occurs for a short period of time before reaching a steady state. This transient current is called the magnetizing inrush current of a transformer, and it is caused by energy transfer that quickly saturates the transformer core. There are other forms of inrush as well, such as recovery inrush and sympathetic inrush. Recovery inrush occurs when transformer voltage recovers to healthy levels following a fault condition. Sympathetic inrush can occur on a transformer when another transformer operating in parallel is energized. Energization inrush is the most commonly investigated form of inrush. It results in a large current magnitude that can lead to voltage sags [1] [2] [3].

A voltage sag, according to IEEE 1159-1995, is a momentary decrease of 10 to 90 percent in the root-mean-square (rms) voltage magnitude for a duration of 0.5 cycles to 1 minute [4]. This paper analyzes the voltage sags that occurred during a simulated transformer energization study for an offshore platform. Fig. 1 shows a simple one-line diagram of the offshore platform comprising Platforms B, B2, and B3. LAN-1600, LAN-1610, and LAN-1620 are gas engine generators, LAN-1750 is a diesel engine generator, and LAN-5200 and LAN-5220 are gas turbine generators.

As a part of the Platform B3 startup sequence, the 1.5 MVA B2-B3 tie transformer (0.48/4.16 kV) and the 3.75 MVA B3-T1 transformer (0.48/0.48/4.16 kV) have to be energized sequentially. During this time, two out of the four generators on Platforms B and B2 are expected to be in service under normal conditions, and all four generators can be in service under maximum operating conditions. Transformer energization typically draws large inrush currents, which can result in voltage sags in the power system. The concern is that these voltage sags might cause other critical loads on the platform to trip due to undervoltage. Another concern is whether the generators are sized adequately to meet the required MVAR demand of the transformer energization.

Under normal operating conditions, the transformers can be energized from the generators on Platform B3 (LAN-5200 and LAN-5220). These generators are rated at 4 MVA/4.16 kV/0.8 power factor (PF). Preliminary simulations were performed to ensure that energization of transformers from these generators did not produce significant voltage sag.

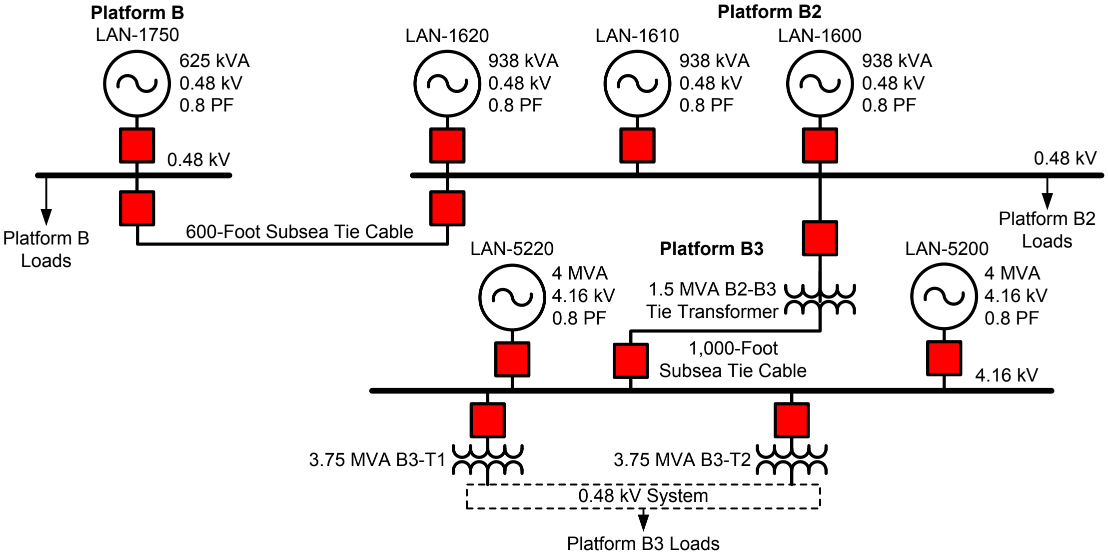


Fig. 1 Simplified One-Line Diagram of Power System

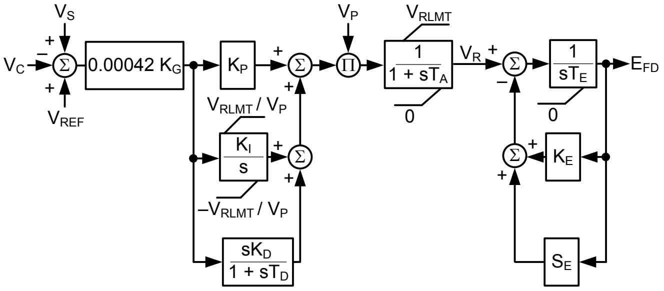
## II. MODELING METHODOLOGY

A power system model was created in a simulation program and was then used to simulate transformer energization under different operating scenarios and to measure the voltage sag. The power system model comprises six generators (three gas engine generators, one diesel engine generator, and two gas turbine generators). The three gas engine generators are rated at 0.48 kV/750 kW/938 kVA/0.8 PF, whereas the diesel engine generator is rated at 0.48 kV/500 kW/625 kVA/0.8 PF. Note that the ratings mentioned here are prime ratings and that overload capability is available for a limited time. The generators were modeled with their automatic voltage regulators (AVRs) and governors. Hence, the simulation accounts for the effects of AVR and governor characteristics on transformer inrush and voltage sag. The model comprises generators, cables (to model the source impedance), transformers, and loads. The loads were modeled as static loads. This level of modeling provided a fairly accurate depiction of system voltage, frequency, generator power output, and AVR and governor responses during transformer energization. References [1], [2], [3], and [5] provide a good description of the physics behind transformer energization.

The inrush current of the transformer is determined by the following factors:

1. Residual flux of the transformer core.
2. Point on the voltage wave at which the transformer is energized.
3. Magnitude of the source impedance.
4. Magnitude of the transformer leakage impedance.
5. Magnitude of the transformer air-core reactance.
6. Transformer knee-point voltage.
7. BH characteristics of the transformer core material.

Fig. 2 shows a dynamic model of the AVR and the excitation system. The diesel and gas engine generators on Platforms B and B2 have a permanent magnet direct current (PMDC) generator attached to the rotor terminals. The voltage output of these PMDC generators is provided as a power input to the AVR. The AVR measures the generator terminal voltage and compares the measured voltage to the reference voltage. An error signal is provided as an input to a proportional integral derivative (PID) control loop. The output of the PID control loop modulates the power input signal from the PMDC generator. This modulated dc voltage is provided to the field winding of the main ac exciter. The output voltage of the main ac exciter provides the field voltage to the main generator [6].



$V_C$ – Measured Voltage
$V_S$ – Voltage Stabilizer Output
$V_{REF}$ – Reference Voltage
$V_P$ – Input From PMDC Generator for Excitation System
$V_{RLMT}$ – Forcing Limit
$V_R$ – Regulated Voltage
$K_G$ – Gain Constant
$K_P$ – Proportional Constant
$K_I$ – Integral Constant
$K_D$ – Derivative Constant
$T_D$ – Time Constant
$T_A$ – Armature Time Constant
$T_E$ – AC Exciter Time Constant
$K_E$, $S_E$ – AC Exciter Saturation Factors
$E_{FD}$ – Generator Field Voltage Input

Fig. 2 Block Diagram of the AVR

Because the transformer is located close to the generation, the bus voltage is depressed during transformer energization. The AVR tries to increase the field current to increase the generator terminal voltage to its reference set point. The dynamic response of the AVR influences the bus voltage magnitude and creates transient oscillations based on its parameters. The AVR model includes a PID control loop and internal limiters. The AVR model has an impact on the power system voltage response and eventually affects the magnitude and duration of the voltage sag [6].

In order to determine the inrush currents, the transformer was modeled using a saturation model. A saturation model is different from the typical equivalent circuit for a two- or three-winding transformer. The equivalent circuit assumes that the magnetizing impedance is a constant value, whereas the saturation model treats the magnetizing inductance as a nonlinear element. The saturation model of the transformer is shown in Fig. 3. As this figure shows, the magnetizing branch ($L_{MAG}$) is located at one end of the winding [7].

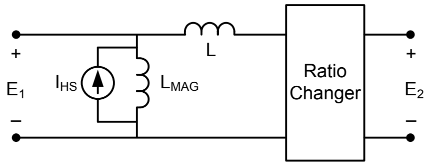


Fig. 3 Saturation Model of the Transformer

In this model, *L* is the transformer leakage reactance. A changeable current source ($I_{HS}$) is placed parallel to the magnetizing branch, and this current source emulates the effect of transformer saturation. $E_1$ and $E_2$ are the primary and secondary voltages of the transformer, respectively. Some of the parameters used to model the transformer have a large impact on the inrush current drawn by the transformers. These parameters are typically not included for standard models in steady-state power system study applications. The parameters specifically included for this application are as follows:

1. Air-core reactance. The air-core reactance limits the peak inrush current. During energization, the transformer core may become saturated and the air-core reactance limits the inrush current.
2. Knee-point voltage. This parameter represents the level of voltage required to reach the knee point on the flux-versus-current characteristic.
3. Flux-versus-current curve (BH curve) loop width. The loop width is used to represent the transformer core losses. The loop width was estimated from the test reports of transformer core hysteresis loops [7].

The BH curve of the 1.5 MVA B2-B3 tie transformer is shown in Fig. 4. The loop width parameter and knee-point voltage determine the shape of this curve. These parameters were obtained from the core material test reports. The curve in Fig. 4 was generated during simulation by plotting the transformer magnetizing current with the transformer flux.

Fig. 5 shows the plot of the BH curve during transformer energization. The magnetizing current for this case increases to approximately 9 kA, whereas the normal magnitude under a steady-state condition is approximately 30 A. During energization, there is a point at which increasing the magnetic field intensity does not result in an increase in flux density. At this point, all of the magnetic domains in the transformer core are aligned and the increasing current does not result in increasing flux. In other words, when the transformer core is saturated, the inductance of the magnetizing branch is reduced [1] [3] [5].

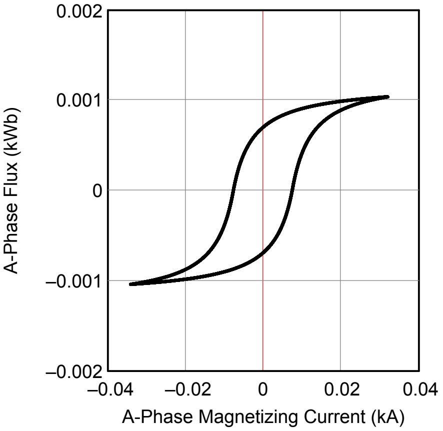


Fig. 4 1.5 MVA B2-B3 Tie Transformer BH Curve

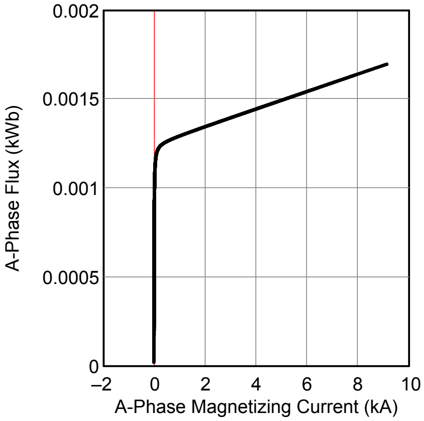


Fig. 5 1.5 MVA B2-B3 Tie Transformer BH Curve During Energization

The energization current drawn by the transformer is determined by the flux, which is proportional to flux density. This, in turn, is determined by the residual flux present in the core and the voltage applied to the transformer. Maximum flux develops when the transformer is energized at the positive zero crossing voltage and the transformer has positive residual flux (or when it is energized at the negative zero crossing voltage and the transformer has negative residual flux). Under this condition, the flux increases for the first half-cycle and saturates the transformer core. When the transformer core is saturated, the magnetizing branch reactance is close to zero and the inrush current is largely limited by the source impedance, transformer air-core reactance, and leakage impedance. These determine the peak inrush current and also the duration (decay) of the inrush current. Generally, the source impedance is much larger than the leakage reactance of the transformer, and the decay time of the transformer inrush is largely determined by the X/R ratio of the source [1].

The worst-case inrush currents were simulated using the following conditions:

1. The transformer was de-energized close to the voltage maximum and, hence, the residual flux present in the core was also at its maximum. However, residual flux decays over time and is usually between 20 to 80 percent of the maximum flux. The BH curve loop width shown in Fig. 4 also influenced the quantity of residual flux in the transformer core at the instant of de-energization.
2. The transformer was energized close to a voltage of zero. The flux was proportional to the voltage and could theoretically rise up to 2.9 times the rated maximum flux. (This is a possibility when residual flux is 0.9 pu, and the flux rises to 2.9 times when the sinusoidal voltage applied across the transformer core rises from zero to the maximum voltage and then decreases from the maximum voltage to zero.) This high flux value was sufficient to drive the transformer core into saturation.

## III. SIMULATION

The two transformers (1.5 MVA B2-B3 tie transformer and 3.75 MVA B3-T1 transformer) were energized under several scenarios defined by various combinations of generators and loads. A waveform for energization under Scenario 1 for the 1.5 MVA B2-B3 tie transformer is shown in Fig. 6.

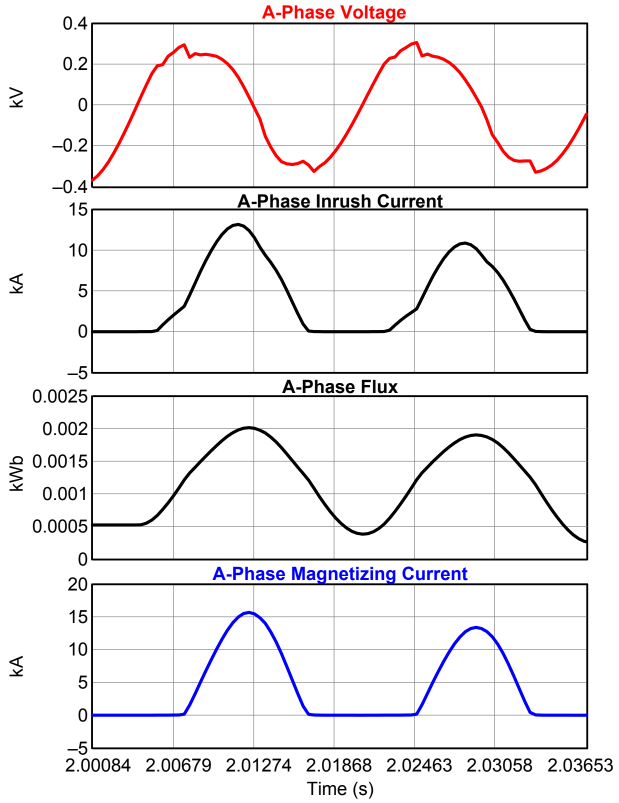


Fig. 6 Energization Waveforms for Scenario 1 on the 1.5 MVA B2-B3 Tie Transformer

In this scenario, LAN-1600, LAN-1610, LAN-1620, and LAN-1750 were in service during energization and the load on the platform was at its minimum. The waveforms captured included bus voltage, A-phase inrush current, A-phase flux, and A-phase magnetizing current.

These quantities are summarized for each scenario in Table I and Table II. These tables provide the voltage sag magnitude, the minimum line-neutral (L-N) rms voltage, the magnitude of the peak inrush currents, and the duration of the voltage sag for all of the scenarios listed.

TABLE I
SUMMARY OF 1.5 MVA B2-B3 TIE TRANSFORMER ENERGIZATION RESULTS (VOLTAGE SAG MEASUREMENTS)

| Scenario | Generators in Service | Total Load (%) | L-N Voltage (%) | Maximum Inrush Current (kA) | Duration of Voltage Sag (s) |
|---|---|---|---|---|---|
| 1 | LAN-1600<br>LAN-1610<br>LAN-1620<br>LAN-1750 | 0 | 78.70 | 11.8 | 0.2 |
| 2 | LAN-1600<br>LAN-1610<br>LAN-1620<br>LAN-1750 | 100 | 79.80 | 12.3 | 0.25 |
| 3 | LAN-1600<br>LAN-1610<br>LAN-1620 | 0 | 75.10 | 11.2 | 0.2 |
| 4 | LAN-1600<br>LAN-1610<br>LAN-1620 | 50 | 74.00 | 12.8 | 0.25 |
| 5 | LAN-1600<br>LAN-1610 | 0 | 66.80 | 9.8 | 0.2 |
| 6 | LAN-1600<br>LAN-1610 | 50 | 67.15 | 11 | 0.3 |
| 7 | LAN-1600 | 0 | 58.12 | 6.06 | 0.2 |
| 8 | LAN-1600 | 20 | 59.60 | 6.3 | 0.35 |
| 9 | LAN-1750 | 0 | 65.00 | 5.25 | 0.3 |
| 10 | LAN-1750 | 20 | 62.80 | 5 | 0.6 |

Energization of the two transformers can cause the generators to operate beyond their rated limits for a long duration, as shown in the waveforms for machine reactive power in Fig. 7. The overexcitation trip for the gas engine generators is set at 2 times the rated field current with a 10-second time delay. The rated field current is defined as the field current that is required to produce the rated kVA at the rated PF and voltage. The waveform shown in Fig. 7 shows the reactive power (Q) and field current (pu) measurements for the gas engine generator LAN-1600. As a reminder, the rating of this generator is 938 kVA/0.48 kV/0.8 PF. Hence, at full load the generator is expected to produce 750 kW and 561 kVAR. The rated field current of this generator in per-unit terms is 2.5 pu.

A field current of 1 pu is the current required to produce the rated voltage at the generator terminal with an open circuit [6]. In the scenario shown in Fig. 7, the simulated generator provided 500 kVAR reactive power before energization and the field current was 2.3 pu. Following energization, the simulated field current increased to 5.5 pu and the reactive power increased to 1.8 MVAR. The field current exceeded its rated value for less than 10 seconds, hence, there is no risk of an overexcitation trip expected for this scenario.

TABLE II
SUMMARY OF 3.75 MVA B3-T1 TRANSFORMER ENERGIZATION RESULTS (VOLTAGE SAG MEASUREMENTS)

| Scenario | Generators in Service | Total Load (%) | L-N Voltage (%) | Maximum Inrush Current (kA) | Duration of Voltage Sag (s) |
|---|---|---|---|---|---|
| 1 | LAN-1600<br>LAN-1610<br>LAN-1620<br>LAN-1750 | 0 | 84.80 | 1.3 | 0.35 |
| 2 | LAN-1600<br>LAN-1610<br>LAN-1620<br>LAN-1750 | 100 | 84.10 | 1.4 | 0.4 |
| 3 | LAN-1600<br>LAN-1610<br>LAN-1620 | 0 | 84.80 | 1.27 | 0.4 |
| 4 | LAN-1600<br>LAN-1610<br>LAN-1620 | 50 | 84.10 | 1.23 | 0.45 |
| 5 | LAN-1600<br>LAN-1610 | 0 | 80.90 | 1.1 | 0.6 |
| 6 | LAN-1600<br>LAN-1610 | 50 | 80.10 | 1.08 | 0.75 |
| 7 | LAN-1600 | 0 | 76.90 | 0.7 | 0.7 |
| 8 | LAN-1600 | 20 | 75.80 | 0.73 | 1.3 |
| 9 | LAN-1750 | 0 | 76.90 | 0.62 | 1.1 |
| 10 | LAN-1750 | 20 | 74.40 | 0.6 | 2.3 |

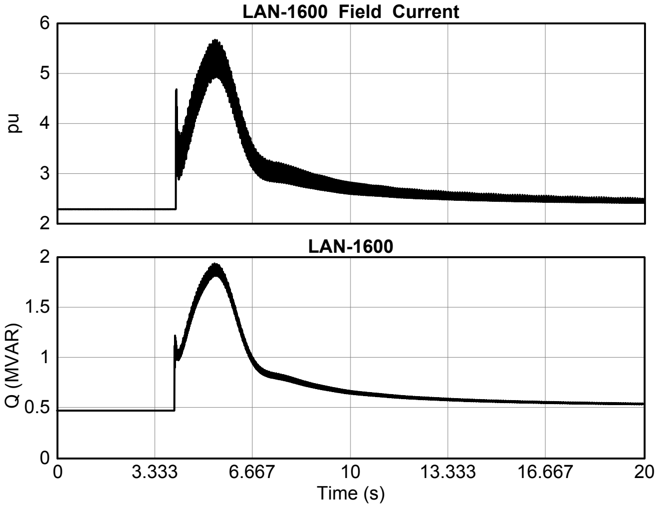


Fig. 7 Reactive Power Output of LAN-1600 for Scenario 8 on the 3.75 MVA B3-T1 Transformer

Following a voltage sag, the AVR tries to force the voltage back to the reference value. This can lead to voltage swells after the voltage sag. The voltage swells can last for several cycles and, if they are large enough, can result in the V/Hz or overvoltage elements in the generator protection relay picking up and tripping. This is shown in the machine terminal voltage waveform in Fig. 8 for Scenario 9 for the 3.75 MVA B3-T1 transformer.

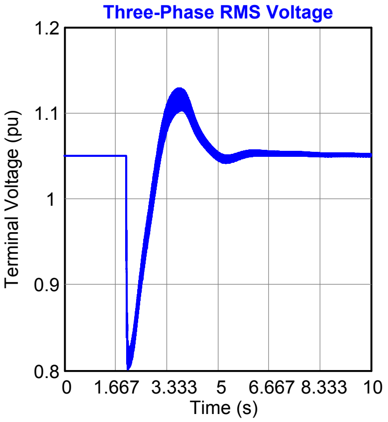


Fig. 8 Terminal Voltage of LAN-1750 for of the Scenario 9 3.75 MVA B3-T1 Transformer

Table I and Table II are useful for interpreting the various factors that influence the magnitude and duration of voltage sag and inrush current magnitude. Energization of both transformers with two or more generators reduces the voltage to less than 80 percent of rated voltage. However, the voltage recovers to 95 percent of its rated value in less than 1 second under no-load and maximum-load conditions on Platforms B and B2.

Voltage drop is less severe when more generators are online and connected to the bus during energization. The maximum voltage drop (40 percent) was observed when energizing the 1.5 MVA B2-B3 tie transformer with one generator (diesel or gas engine generator), as in Scenario 7. However, the duration of voltage sag was only 0.2 seconds.

The source impedance plays a major role in transformer energization. It not only affects the peak magnitude but also the duration of the inrush current. When the source impedance is large, the peak magnitude of the inrush current is lower but the duration of the inrush depends on the system X/R ratio [8]. The observations in this study were consistent with this phenomenon. Energization of the 1.5 MVA B2-B3 tie transformer draws a higher inrush current than the energization of the larger 3.75 MVA B3-T1 transformer. This is because the source impedance for the energization of the B3-T1 transformer is much larger than that of the B2-B3 tie transformer. However, the X/R ratio of the source impedance for the B3-T1 transformer is much larger, and it takes a longer time for the inrush to decay. Consequently, the voltage sag lasts longer and the generators are subject to a longer duration of field-forcing currents, even though the magnitude of the inrush current is smaller.

Energization of the 3.75 MVA B3-T1 transformer draws inrush currents that can last for several seconds before decaying. The AVR increases the field current and tries to return the machine terminal voltage back to the reference value. Because of field forcing, the reactive power output of the machine exceeds its rated value. During energization, the machines provide more VARs than the limits shown in the generator characteristic curve. This is typically acceptable for a short duration. The set point for the AVR was used to determine the overexcitation limits of the generator. The AVR was set to trip on overexcitation. The pickup set point was 2 times the maximum full load field current, and the time delay for the overexcitation trip was set at 10 seconds. The generator field current and voltage plots were used to confirm that the overexcitation trip element would not operate during transformer energization.

Another factor under consideration in this system was the actions of the AVR. When the voltage drops, the controller attempts to drive a large field current and provide additional excitation to the generator [8]. Once the inrush current decays, the AVR overshoots, and this results in voltage swells. Based on simulations, the observed voltage swells are limited to 110 to 115 percent of the rated voltage. No V/Hz protection or overvoltage elements tripped for any of the simulations.

## IV. RECOMMENDATIONS FOR TRANSFORMER ENERGIZATION

Based on this study, certain recommendations were provided for plant operations prior to transformer energization. Energization of the transformers with two or more generators produces voltage sags of lower magnitudes and shorter durations than the energization of the transformers with one generator. Field forcing may also have to be applied for a long time when energizing the transformer with just one generator. The undervoltage pickup settings of the generator protection relay have to be set with a time delay to prevent the relay from tripping during energization. The results shown in Table I and Table II were compared to the undervoltage set points of motor contactors and critical loads on the switchgear to prevent a loss of load during energization.

Energization with a larger reference voltage set at 1.05 pu can produce voltage swells that lead to a V/Hz element trip. However, the simulation results indicate that voltage swells do not exceed 1.15 times the rated voltage. The magnitude of voltage swells is dependent on several factors, including the following:

1. Saturation of the exciter and synchronous generator.
2. Forcing limits of the AVR.
3. Voltage drop magnitude at the machine terminals.
4. Duration of the voltage sag prior to the voltage swell.

Both the 1.5 MVA B2-B3 tie transformer and the 3.75 MVA B3-T1 transformer can be energized with at least two generators in service. The duration of voltage sag produced during the energization of the transformers is expected to last for less than 1 second before returning to a healthy voltage. The settings of the undervoltage contactors of the motors and the undervoltage pickup set points of the generators have to be adjusted to ride through this voltage sag. Machine reactive power output and field currents exceed the rated values because of field forcing for less than 3 seconds when the transformers are energized with two or more generators. This overload is within the generator capability and is not expected to cause an overexcitation trip. Voltage swells are a concern only under certain conditions and do not exceed 1.15 times rated voltage. The machine saturation, field forcing limits, and magnitude and duration of the voltage drop influence the magnitude of the voltage swells following transformer energization.

Accidental energization of the transformers is possible. During a black start, if the B2-B3 tie breaker is left in the closed position, Bus B2 is dead, and the diesel engine generator is used to energize Bus B2, and the 1.5 MVA B2-B3 tie transformer could be accidentally energized with just one generator online. Therefore, protection relaying interlocks were developed to ensure that the B2-B3 tie breaker cannot be closed when Bus B2 is dead and the tie cable between Platforms B2 and B3 is dead. This breaker can be closed only when either Bus B2 or the B2-B3 tie cable is energized (when B3 is live and the B2-B3 tie breaker is closed). Further, in order to prevent simultaneous energization of the 1.5 MVA and 3.75 MVA transformers, all tie breakers and transformer protection breakers must be opened before initiating the black-start sequence.

Inrush currents are reduced when transformers are energized with a higher tap setting. This is applicable for both the 1.5 MVA B2-B3 tie transformer and the 3.75 MVA B3-T1 transformer.

## V. CONCLUSIONS

Voltage sag analysis for an offshore platform during energization of the transformer with parallel generator operation is beneficial because possible protection-related trips and voltage stability issues can be identified and analyzed. The results of this study were used to determine the undervoltage set points for the generator protection relays. Operational procedures and breaker closing interlocks were developed to ensure that transformer energization does not result in a generator overexcitation trip, generator undervoltage trip, overvoltage trip, generator high-temperature trip, undervoltage trip of motor contactors, or voltage instability. Based on this study, it was established that no special design specifications are required for the power transformers in this scenario. Transformer energization studies similar to the one described in this paper can be beneficial for offshore platforms when transformers are energized from limited generation and no utility connection is available.

Performing dynamic studies early for important and large projects is essential and can be performed easily with modern tools to ensure and predict power system performance prior to energization. Undersized equipment cannot be easily replaced or corrected once it is installed, and plants or facilities are often on tight schedules to become operational. These types of studies are vital for determining the allowable operating conditions of the power systems that supply critical and continuous processes. They also help with designing the protection and control schemes for these systems.

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## VII. VITAE

**Srinath Raghavan** received his B.S. in 2009 from Anna University in India and his M.S. in electrical engineering from Missouri University of Science and Technology in 2013. His research encompassed power system modeling and analysis. Srinath worked as a protection engineer in Areva T&D in Chennai, India, where he was involved in the commissioning of protection systems. In 2013, he joined Schweitzer Engineering Laboratories, Inc. as a protection engineer. He is a registered professional engineer in the state of Texas.

**Bruce J. Hall** received his B.S. (cum laude) in electrical and mechanical engineering in 2011 from Michigan Technological University. Upon graduation, he joined Marathon Oil Company as a facility/project engineer. He is involved with the engineering, construction, and commissioning of an offshore gas compression platform. His current responsibilities consist of the design and implementation of a new power management system to integrate the new platform’s power system into the existing facilities.

**Rekha T. Jagaduri** received her B.S. in 2003 from Madras University in India and her M.S. (magna cum laude) in power systems from Tennessee Technological University. She worked as a power system engineer in the protection and control division for the EPC Company in Knoxville, Tennessee. Rekha has utility company and research experience. She has been involved in electric power engineering protection and control design, solution development, and detailed engineering design. In 2008, Rekha joined Schweitzer Engineering Laboratories, Inc. She has led large industrial projects, is a member of IEEE, and has authored various technical papers. She is a registered professional engineer in the state of Texas.

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