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LOAD VARIATION ANALYSIS OF GENERATOR ON LEMBAR-PADANG BAI RO-RO SHIPS FOR SAFETY MARITIME

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***Abstract*— The Lembar-Padang Bai route is a crucial and frequently used maritime passage, accommodating up to 54 daily crossings, as Direct Ferries reported. Given the high frequency of operations, maintaining the optimal operational readiness of vessels on this route is critical for ensuring smooth and reliable voyages. One of the essential components for stable ship operations is a reliable electrical system, primarily powered by onboard generators. This study focuses on six operational scenarios affecting the electrical system of Ro-Ro vessels on the Lembar-Padang Bai route. These scenarios include: (1) Single Motor Start Manoeuvre Condition (Air Compressor), (2) Single Motor Start Manoeuvre Condition (Electric Bow Thruster), (3) Single Generator on Manoeuvre Condition, (4) Short Circuit Manoeuvre Condition in Hull Compartment Bus, (5) Single Generator off Manoeuvre Condition, and (6) Manual Load Shedding Manoeuvre Condition on the Emergency Generator Room Bus. The analysis was conducted using the Electrical Transient Analysis Program (ETAP) to assess the effects of varying load conditions on voltage and frequency stability. The results indicate that the air compressor motor does not significantly impact the electrical system's stability. However, the electric bow thruster motor caused a significant voltage drop, reducing voltage to 85%, highlighting the importance of robust load management. In cases of manoeuvring, it is recommended that three generators be added to the system to maintain stable voltage and frequency levels. During short circuit conditions, rapid load shedding is essential to prevent severe voltage drops and ensure the system remains within standard operating parameters.**

Keywords— Voltage Stability, Load Management, ETAP, Maritime Safety, Ro-Ro Ferry, Electrical System Analysis

I. INTRODUCTION[1]

The Lembar-Padang Bai route is a crucial and frequently used maritime passage, accommodating up to 54 daily crossings,as Direct Ferries reported [1]. Given the high frequency of operations, maintaining the optimal operational readiness of vessels on this route is critical for ensuring smooth and reliable voyages. One of the essential components for stable ship operations is a reliable electrical system, primarily powered by onboard generators.

During significant disturbances such as short circuits, the angular displacement between generator rotors can increase uncontrollably, potentially leading to a loss of synchronism in one or more generators. This phenomenon, known as transient stability, primarily affects the generator closest to the disturbance point. Therefore, in any stability analysis, assessing the impact of such faults on the system's transient stability and evaluating the system's ability to return to a stable operating condition following the disturbance[2].

The electrical power system on a ship is subject to highly dynamic and rapidly fluctuating load demands that can vary from moment to moment. Despite these fluctuations, the power supply must remain stable and continuously meet load requirements. A sudden surge in load can result in a frequency drop within the system. Similarly, the failure or tripping of a generator unit may also lead to a decrease in system frequency.[3].

Voltage stability refers to the capacity of an electrical power system to maintain acceptable voltage levels under both normal operating conditions and following disturbances. In addition to disturbances, factors such as increased load demand and alterations in system configuration can significantly impact voltage stability. If the system fails to maintain stability, the voltage at the receiving end may decline below acceptable thresholds, potentially leading to a phenomenon known as voltage collapse. This condition is characterized by a drastic reduction in voltage, which can result in a partial or complete blackout of the system[4].

Several factors that need to be considered in the analysis of voltage and frequency stability in shipboard electrical systems include:

A. Disturbances That Affect Stability

Several types of disturbances can impact the stability of an electrical power system:

1. Short Circuit Faults – These faults typically arise from lightning strikes, insulation breakdowns, or damaged equipment. A short circuit results in an excessive current surge, which can compromise system stability and

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potentially damage equipment if not addressed promptly[5].

2. Motor Starting Faults – The initiation of large motors often draws currents that are 4 to 6 times greater than their normal operating levels. This surge can cause significant voltage drops, adversely affecting the system’s stability. Frequent voltage dips can accelerate equipment degradation, making implementing appropriate motor starting techniques essential[5].
3. Sudden Load Additions – Rapid addition of excessive loads, particularly those exceeding the system’s capacity, can lead to abrupt increases in current and corresponding drops in voltage and frequency. Such conditions may disrupt the synchronization between components. If the generator’s mechanical input cannot meet the increased electrical demand, it may result in a loss of system stability[6].

B. Voltage and Frequency Operation Limits Standard

Biro Klasifikasi Indonesia (BKI) is a state-owned classification society responsible for regulating and certifying the seaworthiness of vessels operating within Indonesian waters. Its scope of evaluation encompasses various aspects of ship safety, including the hull’s structural integrity, mechanical systems, and electrical installations. Specifically for electrical systems, BKI establishes voltage and frequency standards as stipulated in Volume IV of the *BKI Rules for Ship Electrical Installations*. These standards are designed to ensure the operational reliability and seaworthiness of ships by defining acceptable voltage and frequency limits for both AC and DC systems across a range of operating conditions, as detailed in the following tables[7].

TABLE 1.
STANDARD VOLTAGE AND FREQUENCY VARIATIONS FOR AC DISTRIBUTION SYSTEMS

Quantity in Operation	Variations	
	Permanent	Transient
Frequency	+/- 5%	+/- 10% (5 sec)
Voltage	6% - 10%	+/-20% (1.5 sec)

TABLE 2.
STANDARD VOLTAGE VARIATIONS FOR DC DISTRIBUTION SYSTEMS

Parameters	Variations
Voltage tolerance (continuous)	+/- 10%
Voltage cyclic variation deviation	5%
Voltage ripple (a.c.r.m.s over steady d.c voltage)	10%

C. Electrical Transient Analysis Program (ETAP) Software

The Electrical Transient and Analysis Program (ETAP) is a comprehensive software application designed for the modelling, analysis, and management of electrical power systems. It supports both offline and online modes of operation—allowing users to simulate the behaviour of electrical systems under various conditions, as well as to monitor and control real-time system performance. ETAP offers a wide range of analytical tools, including modules for evaluating power generation, transmission networks, and electrical distribution systems, making it an essential tool for system planning, operation, and optimization[8][9].

The novelty obtained based on the literature review [1-6] is that proper load management, such as managing the compressor motor and electric bow thruster motor during manoeuvring conditions while adhering to voltage and frequency standard limits, can be identified through six case study simulations implemented using ETAP software. This approach enables the determination of effective protective mechanisms to maintain the safety and reliability of the ship’s electrical system. These findings underscore the importance of precise load management and protective mechanisms to enhance the safety and reliability of maritime electrical systems.

II. METHOD

A. Field Observation

Field observation was conducted to collect data through interviews with the Owner Surveyor of the Lembar-Padang Bai Ferry.

B. Data Collection

TABLE 3.
SHIP PARTICULARS

Type of Ship	: Ferry Ro-Ro
Tonnage (GT)	: 1500 GT
LOA	: 77,72 m
LBP	: 72,60 m
B	: 14,00 m
H	: 4,60 m
T	: 3,30 m
Vs	: 15 knots
Main Engine	: 2 x 1350 kW
Auxiliary Engine	: 3 x 416 ekW (520 kVA)
Bow Thruster	: 1 x 335 ekW

TABLE 4.
SPECIFICATIONS OF BAUDOUIN 6 M26.2 GENERATOR

Model	Injection	Speed Control	Cylinder Config	Bore/Stroke (mm)	Displacement (I)
6M26.2	Mechanical	Electronic	6 in line	150x150	16
Rating	Frequency	RPM	kWm	kWe	kVA
PRP	50 Hz	1500	440	416	520

C. Circuit Modelling

Circuit modelling is performed by gathering relevant data and utilizing the Electrical Transient Analysis Program (ETAP) software. The primary objective of this modelling is to design an electrical system that can be effectively simulated and analysed. A single-line diagram of the circuit, developed using ETAP, is illustrated in Figure 1 bel ow.

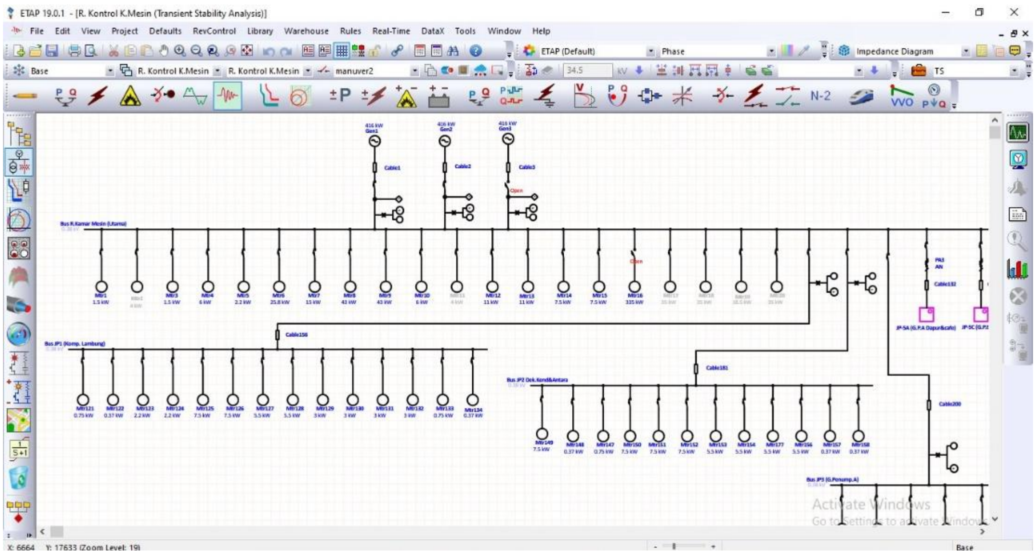

Figure 1. Single Line Diagram Lembar-Padang Bai Ro-Ro Ship

D. Study Cases of Voltage and Frequency Stability Analysis

Based on the developed circuit model, simulations were conducted according to the specified case study scenarios. These simulations' resulting voltage and frequency values were analysed to assess system stability. The table below outlines the case study scenarios utilized for this analysis:

TABLE 5.
STUDY CASE PLANNING

No.	Study Case	Explanation/Annotation
1	Single Motor Start Manoeuvre Condition (Air Compressor)	The air compressor on the emergency generator room bus is started at the 2-second mark while two generators are running.
2	Single Motor Start Manoeuvre Condition (Electric Bow Thruster)	The electric bow thruster on the emergency generator room bus is started at the 5-second mark while two generators are running.
3	Single Generator on Manoeuvre Condition	Generator three is turned on when the system has been running for 10 seconds.
4	Short Circuit Manoeuvre Condition in Hull Compartment Bus	A short circuit occurs on the hull compartment bus at the 15-second mark, and the voltage relay response on the hull compartment bus is observed.
5	Single Generator off Manoeuvre Condition	Generator one suddenly disconnects from the system at the 25-second mark.
6	Manual Load Shedding Manoeuvre Condition on Emergency Generator Room Bus	Manual load shedding is performed on the emergency generator room bus at the 30-second mark.

III. RESULTS AND DISCUSSION

A. Simulation Planning of the Case Study on Lintas Lembar–Padang Bai Ship

The study cases discussed in this paper generally include the following scenarios:

1. Motor Starting Occurs

This scenario represents the ship's transition from sailing to port manoeuvring operations (such as entering or exiting the harbour). During this phase, key motors that were initially inactive are started shortly after the system becomes operational. The motors involved include the air compressor and the electric bow thruster, constituting the largest induction motor loads during manoeuvring. The air compressor is scheduled to start 2 seconds after system initialization, followed by the bow thruster at 5 seconds. The system's transient response is then analysed, with particular attention given to voltage and frequency behaviour during the motor start-up sequence.

2. Generator on and off Events

An single generator is active within the system during the transition from sailing to manoeuvring conditions. At 25 seconds, this generator unexpectedly disconnects from the network. The system's transient response will be evaluated to assess whether it remains within acceptable operational limits. Key parameters monitored following the disturbance include voltage and frequency, providing insight into the system's stability and resilience.

3. Short Circuit Occurrence

In this scenario, a three-phase short circuit fault is assumed to occur at one of the buses, specifically the Hull Compartment Bus. Such faults significantly impact the overall stability of the electrical power system. The simulation is conducted under manoeuvring conditions to observe the system's transient response following the fault. The objective is to evaluate whether the voltage and frequency remain within acceptable operational limits during and after the disturbance.

B. Transient Stability Case Simulation

1. Transient Stability Simulation Case: 2 Motors Starting

The result is shown in Figures 2 and 3.

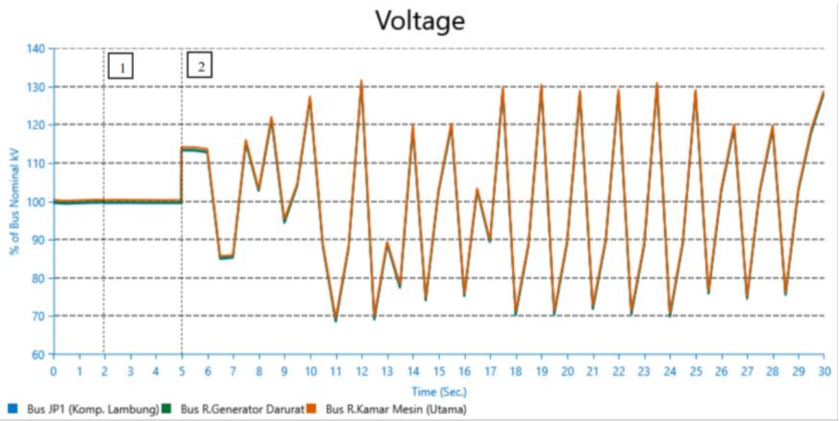

Figure 2. Voltage Response for Transient Stability Case: 2 Motor Starting

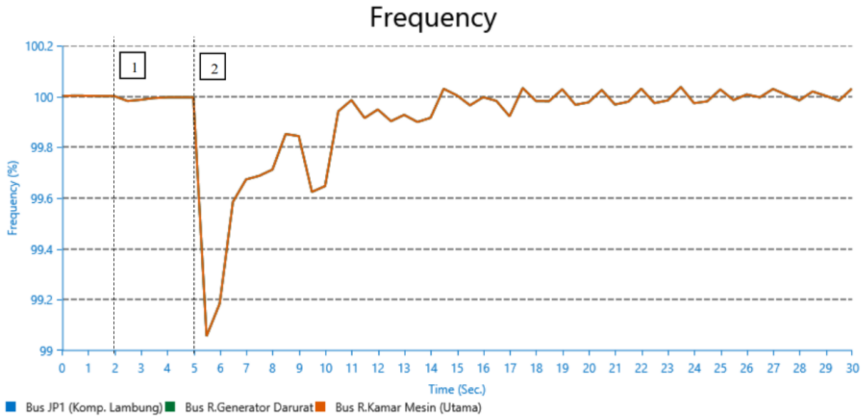

Figure 3. Frequency Response for Transient Stability Case: 2 Motor Starting

TABLE 6.

VOLTAGE AND FREQUENCY RESPONSE FOR TRANSIENT STABILITY CASE: 2 MOTOR STARTING

No.	Result
1	Single Motor Start (Air Compressor) Voltage Response: At the 2-second mark, the air compressor motor with a power of 4.5 kW is turned ON. The voltage response from the 2nd to the 5th second remains stable at 100%. Frequency Response: From the 2nd to the 5th second, the frequency response also remains stable at 100%.
2	Single Motor Start (Electric Bow Thruster) Voltage Response: At the 5-second mark, the Electric Bow Thruster motor with a power of 335 kW is turned ON, causing continuous voltage oscillations. The highest voltage spike reaches 131.6% at the 12-second mark, and the lowest voltage dip is 69.31% at the 11-second mark. Frequency Response: When the 335 kW Electric Bow Thruster is turned ON, the frequency slightly drops to 99.05% at the 5-second mark.

It can be concluded that initiating the 4.5 kW air compressor motor results in negligible voltage and frequency fluctuations. In contrast, starting the 335 kW Electric Bow Thruster leads to significant voltage instability. At approximately 8 seconds, the system voltage peaks at 129% and oscillates. According to transient operation standards, voltage deviations must remain within ±20% and stabilize within 1.5 seconds. Therefore, the voltage behaviour depicted in Figure 1 is deemed unsafe.

The startup of the Electric Bow Thruster motor induces a substantial inrush current, which contributes to voltage drops and compromises system stability. When power (P) remains constant but voltage (V) decreases, the resulting increase in current (I) can cause overheating of cables. This condition may lead to short circuits or even fires. Operating under such unstable voltage conditions is highly inadvisable, as it poses a risk of damage to multiple components within the electrical system [10], Field[11].

2. Transient Stability Simulation Case: 2 Motors Starting and 1 Generator On (Emergency Generator)
The result is shown in Figure 4 and Figure 5

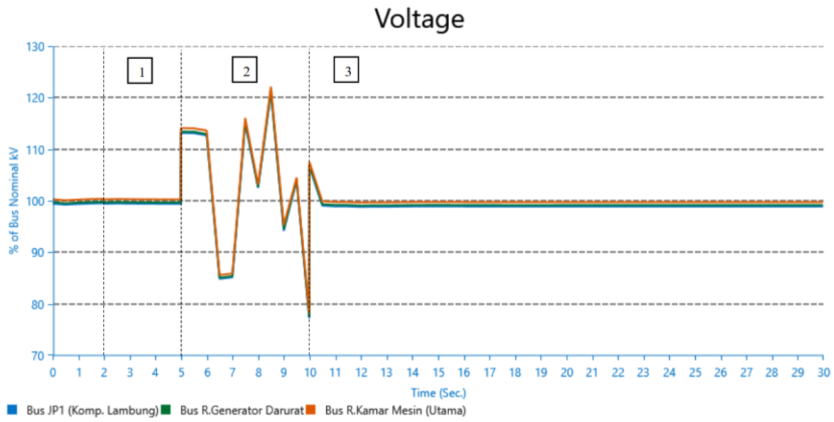

Figure 4. Voltage Response for Transient Stability Case: 2 Motor Starting and 1 Generator On

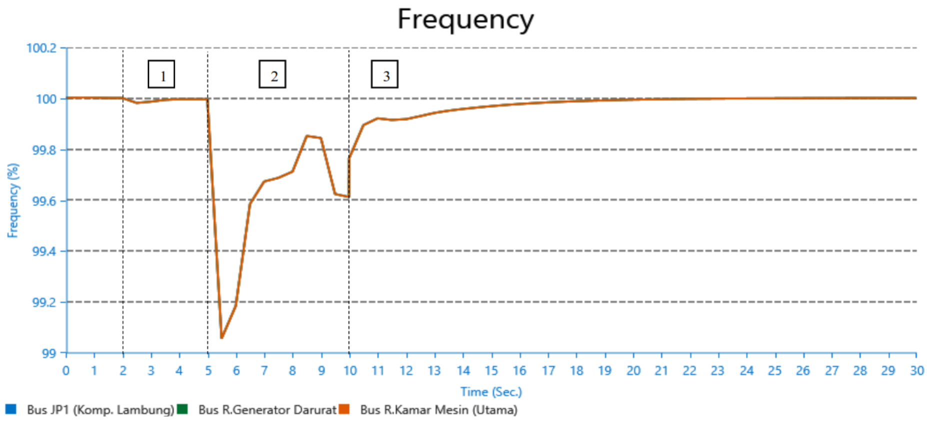

Figure 5. Voltage and Frequency Response for Transient Stability Case: 2 Motor Starting and 1 Generator On

TABLE 7.
VOLTAGE AND FREQUENCY RESPONSE FOR TRANSIENT STABILITY CASE: 2 MOTOR STARTING AND 1 GENERATOR ON

No.	Result
1	Single Motor Start (Air Compressor) Voltage Response: At the 2-second mark, the air compressor motor with a power of 4.5 kW is turned ON. The voltage response remains stable at 100% from the 2nd to the 5th second. Frequency Response: The frequency also stays stable at 100% during this same time frame.
2	Single Generator On (Emergency Generator) Voltage Response: At the 10-second mark, the voltage drops to 78%. When the third generator is connected to the system, the voltage rises to 106.6% and stabilizes at 100% by the 20-second mark. Frequency Response: When the third generator is connected, the system frequency returns to a stable condition. At the 20-second mark, the frequency response is at 100%.
3	Single Motor Start (Electric Bow Thruster) Voltage Response: At the 5-second mark, turning on the 335 kW Electric Bow Thruster causes voltage fluctuations. The voltage peaks at 114% at 5 seconds and dips to 85.5% at 6.5 seconds. Frequency Response: When the 335 kW Electric Bow Thruster is turned on, the frequency slightly drops to 99.05% at 5.5 seconds.

It can be concluded that under manoeuvring conditions, the voltage and frequency responses of the system become unstable when only two generators are connected. Stability is achieved only when three generators are operating in parallel. Therefore, based on standard operational limits, the voltage and frequency conditions are deemed safe and within acceptable thresholds only when three generators are used.

As illustrated in Figure 4, the most significant frequency dip occurs at 5.5 seconds, reaching 90.05% of the nominal value. Given that the transient frequency tolerance is ±10% for up to 5 seconds, this condition approaches the threshold. Consequently, it is recommended that three generators be connected during manoeuvring operations to maintain system stability.

3. Transient Stability Simulation: Short Circuit on Hull Compartment Bus
The result is shown in Figures 6 and 7

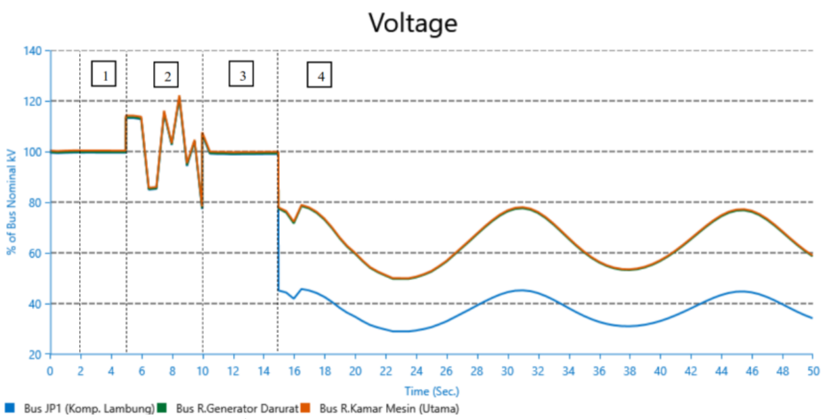

Figure 6. Voltage Response for Transient Stability Case: Short Circuit on Hull Compartment Bus

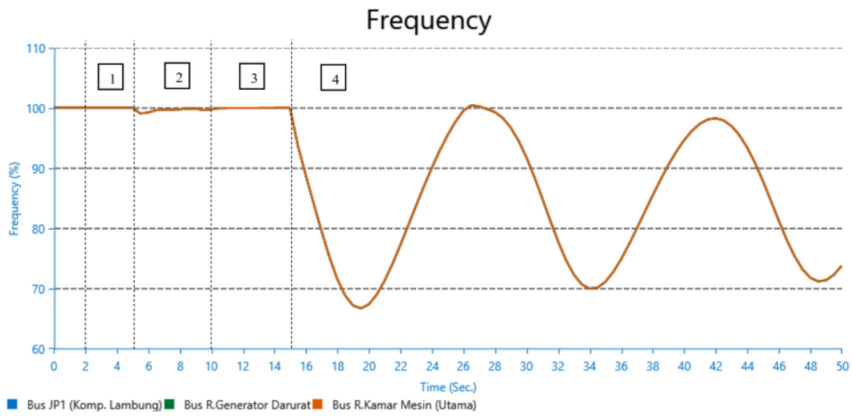

Figure 7. Frequency Response for Transient Stability Case: Short Circuit on Hull Compartment Bus

TABLE 8.
VOLTAGE AND FREQUENCY RESPONSE FOR TRANSIENT STABILITY CASE SHORT CIRCUIT ON HULL COMPARTMENT BUS

No.	Result
1	Single Motor Start (Air Compressor) Voltage Response: At the 2-second mark, the Air Compressor Motor (4.5 kW) is turned on. From the 2nd to the 5th second, the voltage response remains stable at 100%. Frequency Response: From the 2nd to the 5th second, the frequency response also remains stable at 100%.
2	Single Motor Start (Electric Bow Thruster) Voltage Response: At the 5-second mark, the Electric Bow Thruster (335 kW) is turned on, causing voltage fluctuations. The voltage peaks at 114% at the 5-second mark and drops to 85.5% at 6.5 seconds. Frequency Response: When the Electric Bow Thruster is turned on, the frequency slightly drops to 99.05% at 5 seconds.
3	Single Generator On (Emergency Generator) Voltage Response: At the 10-second mark, the voltage is 78%. When the third generator is connected to the system, the voltage rises to 106.6%. Then, at 10.5 seconds, the voltage stabilizes at 100% and remains stable until the 15-second mark. Frequency Response: When the third generator is connected, the frequency returns to a stable condition, remaining at 100% from the 10th to the 15th second.
4	Short Circuit on Hull Compartment Bus Voltage Response: At the 15-second mark, a short circuit occurs on the Hull Compartment Bus, causing a voltage drop in the electrical system. The voltage on the Engine Room Bus (leading) at 15 seconds is 77.8%, while on the Hull Compartment Bus it drops to 45%. Under these conditions, voltage responses on both the Hull Compartment Bus and Engine Room Bus become unstable, with continuous fluctuations. Frequency Response: The short circuit in the Hull Compartment Bus causes frequency instability. The lowest frequency drop occurs at 19.51 seconds, reaching 66.66%, and the frequency recovers back to 100.2% by the 27-second mark.

Under these conditions, the system's voltage and frequency responses are classified as unsafe based on standard operational limits for voltage and frequency. As depicted in Figure 6, the primary bus voltage drops to 77.8% at the 15-second mark and continues to fluctuate below 80%. This exceeds the allowable transient voltage deviation of ±20% for up to 1.5 seconds. Similarly, Figure 7 shows that the system frequency falls to 88.69% at 16 seconds and continues to oscillate. Between seconds 16 and 24, the frequency remains below 90%, exceeding the permissible transient frequency deviation of ±10% for 5 seconds. If the system continues to operate under these conditions, there is a high risk of damage to critical components. Therefore, operation under such voltage and frequency instability is strongly discouraged.

4. Transient Stability Simulation Case: Short Circuit and Load Shedding on Hull Compartment Bus

The result is shown in Figure 8 and Figure 9

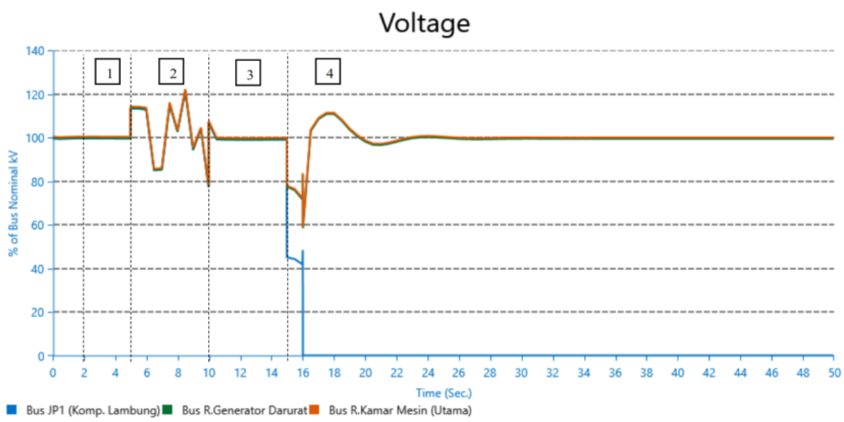

Figure 8. Voltage Response for Transient Stability Case: Short Circuit and Load Shedding on Hull Compartment Bus

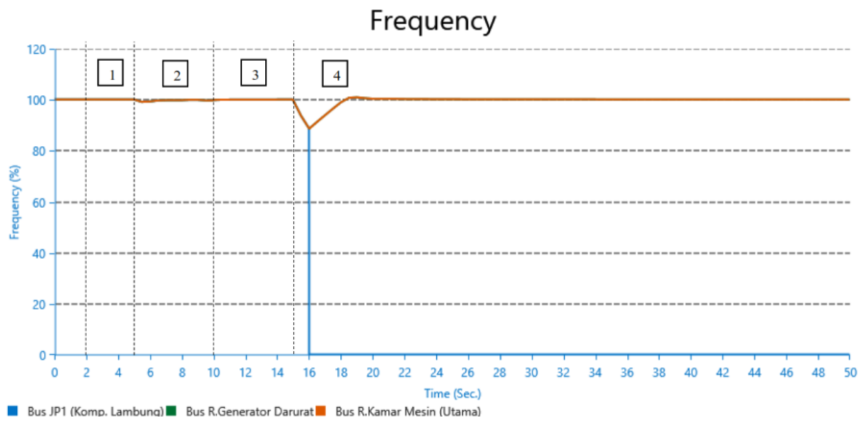

Figure 9. Frequency Response for Transient Stability Case: Short Circuit and Load Shedding on Hull Compartment Bus

TABLE 9

VOLTAGE AND FREQUENCY RESPONSE FOR TRANSIENT STABILITY CASE: SHORT CIRCUIT AND LOAD SHEDDING ON HULL COMPARTMENT BUS

No.	Result
1	Single Motor Start (Air Compressor) Voltage Response: At the 2-second mark, the air compressor motor (4.5 kW) is turned on. The voltage response remains stable at 100% from the 2^{nd} to the 5^{th} second. Frequency Response: From the 2nd to the 5th second, the frequency response also remains stable at 100%.
2	Single Motor Start (Electric Bow Thruster) Voltage Response: At the 5-second mark, the electric bow thruster motor (335 kW) is turned on, causing voltage fluctuations. The voltage peaks at 114% at second 5 and drops to 85.5% at second 6.5. Frequency Response: The activation of the 335 kW motor causes a slight frequency drop to 99.05% at second 5.
3	One Generator On (Emergency Generator) Voltage Response: At second 10, the voltage drops to 78%. When Generator 3 is connected to the system, the voltage increases to 106.6%. By second 10.5, the voltage stabilizes at 100% and remains stable until second 15. Frequency Response: When Generator 3 is connected, the frequency response returns to a stable condition. From second 10 to 15, the frequency remains at 100%.
4	Short Circuit at Hull Compartment Bus + Load Shedding Voltage Response: At second 15, a short circuit occurs on the Hull Compartment Bus, causing the voltage to drop to 77.8%. At second 16, a voltage relay responds by shedding the load on the Hull Compartment Bus. By second 24, the voltage stabilizes at 100%. Frequency Response: At second 16, the frequency drops to 88.8%. At the same moment, load shedding is performed on the Hull Compartment Bus. By second 18.5, the frequency returns to a stable condition of 100%.

The short circuit at the Hull Compartment Bus at the 15-second mark causes the voltage to drop to 77.8%. However, due to the activation of the voltage relay at second 16, the voltage rapidly recovers and reaches 102.68% by 16.05 seconds. According to operational standards, which permit a ±20% voltage deviation for up to 1.5 seconds during transient conditions, this voltage response is still within the acceptable range.

Similarly, the frequency response is also deemed acceptable. Although the frequency drops to 88.8% at second 16, it recovers 100% by second 18.5.

The system's responses under this fault condition are considered stable based on the standard operational limits for both voltage and frequency. While temporary deviations in voltage and frequency are observed, the load shedding mechanism, triggered by protective relays, effectively restores system stability in compliance with the established standards.

IV. CONCLUSION

The operation of the air compressor motor (4.5 kW) does not induce significant voltage fluctuations, indicating stable voltage and frequency conditions. In contrast, starting the electric bow thruster motor (335 kW) causes the voltage to drop to 85% at approximately 6.5 seconds.

During manoeuvring conditions, voltage and frequency responses exhibit instability when only two generators are connected to the system. Stability in both voltage and frequency is attained only when three generators are operational.

Furthermore, a short circuit occurring at the hull compartment bus at the 15-second mark results in a voltage drop to 77% at the engine room bus and 45% at the hull compartment bus. These values indicate an unsafe operating condition for onboard equipment, necessitating the implementation of a load shedding mechanism via a voltage relay to maintain voltage levels within the prescribed standard limits.

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