Unbalanced load analysis on closed bus electrical system of ship’s dynamic positioning in a laboratory scale

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Abstract. Dynamic positioning system is a system that maintains floating offshore structures and ships their position on a certain coordinate that have been prearranged. The dynamic positioning system uses thrusters, which require additional power. As a consequence the fuel consumption is increasing. In the installation of a dynamic positioning system, the configuration of a split bus is usually applied. As of lately, there are a lot of concern in changing to a closed bus configuration because theoretically the system will have high efficiency and low emission. An analysis is performed to observe the condition of unbalance voltage of dynamic positioning system of a ship by modelling in a laboratory scale system. Several scenarios and variations are used to see the condition of the unbalance. The system modelling results in 220V∠0°, 218V∠-113.7°, 218V∠123.18° for scenario 1 variation 1, 220V∠0°, 220V∠-120°, 218V∠120° for scenario 2 variation 1, and lastly 219V∠0°, 220V∠-120°, 220V∠120° for scenario 3 variation 1. The highest unbalance condition happens on scenario 1 variation 3 with a PVUR of 0.78%.

1. Introduction
Dynamic Positioning (DP) system is a system that is used to control the position of a floating offshore structure such as FPSO and oil rigs or a seagoing ship, and also maintain its condition in a stable state on a destined coordinate. The DP system is assisted by an auxiliary system that support the DP system operation. The auxiliary system is the power supply system, control system and thruster system. Due to the operation of those systems, the load that should be supplied by the ship or any offshore structure is increasing [1].

The classification of the DP is divided into 3 classes, with the difference being its redundancy. The difference in configuration is selected to minimize the risk of system failure due to interference with the power system [2]. The dynamic DP usually runs using the split bus configuration in its operation. Though the technology develops rapidly, efficiency and emission of the system is getting noticeable. Because of that, some preference in the configuration of the DP system is shifting to become a closed bus configuration system. The closed bus system is believed would give more efficiency, low maintenance time, and less emission rate [3].

Although there are a lot of positive outcome in using the closed bus system, some are still considering changing because of the problems that could happen. In case failure happens on the main bus system; it could reduce the system redundancy, thus making the system broke down.

This research will be focused on one of the problems that could happen on an electrical system, which is an unbalance voltage. The electrical system in question is a system of an Anchor Handling Tug
Supply (AHTS) vessel. AHTS vessel is a ship that are used as a support for offshore projects and operations by installing a specific system on them [4].

2. Methodology

2.1 System Modelling
Analysis for the system’s unbalance voltage will be done by using a model of the existing system. The system is a Dynamic position system for a ship. The system consists of 3 main generators as its main power supply and 2 motors that acts as the thruster for the DP system. The system will be shown in Figure 1. Two generators are the generators that are used for specifically to give power to the motor thrusters. The other generator is the main generator that is powering the main electrical system for the ship.

![Figure 1. Model of a dynamic positioning system](image)

2.2 Unbalance Voltage
An unbalance voltage is condition where the value of the voltage is not balanced on each of the phases. Other conditions are if the angle of each phase is not 120° [5, 6]. Though if a voltage is not same just by little is called unbalance there are certain conditions in where there are limit on how much an unbalanced are allowed based on its definitions. The stability of this voltage is influenced by large and small disturbance in the short and long term [7].

Major disruption for example is loss of generation or lost synchronization of the generator and short circuit on the system. While minor disturbances are like the addition of small-scale load, so the system seeks to improve itself. There are many possible voltage unbalance conditions in a power system, which are divided into eight cases: single phase under voltage unbalance, two phase under voltage unbalance, three phase under voltage unbalance, single phase over voltage unbalance, two phase over voltage unbalance, three phase over voltage unbalance, unequal single phase angle displacement, and unequal two phase angle displacement [8].

Voltage unbalance could cause many problems such as, the rise of temperature of the induction motors under unbalance voltage, the reduced of motor rating, and efficiency reduction [9]. While usually the cause of unbalance voltage is caused by unbalance load, the cause itself are complex and are categorized onto structural or functional. The former refers to the asymmetry in the three-phase impedance transmission/distribution lines, cables, transformers, etc. it occurs because it is neither economical nor necessary to maintain distribution system with perfectly symmetrical impedances. The latter refers to uneven distribution of power consumption over the three phases [10,11].

Another aspect that could cause an unbalance is due to high neutral currents in distribution transformers which normally result from two situations [12]. The first, and most common, is one where there are simply heavily unbalanced loads. This situaion is usually easy to explain and remedy: loads need to be evenly distributed across the phases to reduce the neutral current. However, in harmonic
environment the situation is different. Whilst positive and negative sequence components of harmonic
current add to zero at enutral point, zero sequence do not. The zero sequence components are additive
at the neutral and are the reason for high neutral current, even though the loads may be perfectly balanced
[13].

2.3 Definitions of Unbalance Voltage
There are three definitions of the following voltage unbalance [14,15]:

2.3.1 NEMA definition
The American standard ANSI C84.1-2206 defines unbalance as the ratio of the maximum voltage
deviation from the average line voltage magnitude to the average line voltage. Definition form NEMA
(National Equipment Manufacturer’s Association) which is known as the line voltage
unbalance ratio \((LVUR)\), can be seen in equations (1) and (2).

\[
\%LVUR = \frac{\text{max} \text{ voltage deviation from the average line voltage}}{\text{average line voltage}} \times 100 \tag{1}
\]

\[
\%LVUR = \frac{\text{Max}[|V_{ab}-V_{avg}|]|V_{bc}-V_{avg}|]|V_{ca}-V_{avg}|}{V_{avg}} \times 100 \tag{2}
\]

The NEMA definition assumes that the average voltage is always equal to its value, where the voltage
is 480 V for an American three-phase system and works only with magnitude, for its angle phase are
not included. ANSI C84.1-2006 [4] recommends that electrical supply system should be designed and
operated to limit the maximum voltage unbalance to 3% when measured at the electric-utility revenue
meter under no load conditions.

2.3.2 IEEE definition
The IEEE uses the same definition of voltage unbalance as ANSI C84.1-2006 with a subtle difference
being that the IEEE uses phase voltage rather than line to line voltages. IEEE Std. 112 uses another
index to quantify voltage unbalance. Definition from IEEE is also known by phase voltage unbalance
ratio \((PVUR)\) can be seen on equations (3) and (4).

\[
\%PVUR = \frac{\text{max} \text{ voltage deviation from the average phase voltage}}{\text{average phase voltage}} \times 100 \tag{3}
\]

\[
\%PVUR = \frac{\text{Max}[|V_{ab}-V_{avg}|]|V_{bc}-V_{avg}|]|V_{ca}-V_{avg}|}{V_{avg}} \times 100 \tag{4}
\]

According to IEEE Std. 112-2004 [3], the voltage unbalance shall not exceed 0.5% for the test
procedure for poly phase induction motors and generators.

2.3.3 True definition
True Definition IEC. The true definition of voltage unbalance is defined as a percentage of the voltage
unbalance factor \((%VUF)\) obtained from the comparison between negative components \((V_n)\) with
positive component \((V_p)\), which is:

\[
\%VUF = \frac{\text{negative sequence voltage component}}{\text{positive sequence voltage component}} \times 100 \tag{6}
\]

Positive sequence voltage are supplied by generators within the system and are always present. A
second set of balanced phasors are also equal in magnitude and displayed 120 degrees apart but display
a counterclockwise rotation sequence which represents a negative sequence. These definitions will be
used to analyze the voltage that is flowing on the system [16].

The maximum \(VUF\) that are allowed is 5%. IEC standards (the IEC 1000-3-x series) give limits for
the unbalance ratio, to be less than 2% for low and medium voltage systems and less than 1% for high
voltage systems measured as 10 minute values. An instantaneous maximum value of 4% is allowed.

2.4 Scenarios and Variations
In analysing the system, several scenarios and variations are used to analyse the system on different possibilities. 3 Scenarios with variations on each scenario are planned. The first scenario is a scenario where 2 generators are used with the load being 2 of the bow thrusters motors. The 2 generators are the thruster generator [17]. For its variation, the load for the motors will be 60% - 75%, 100% - 80%, 100% - 100%, and 110% - 110% respectively.

The second scenario will only use 1 thruster generator with 2 motor being the load. The loads are 40% - 40%, 50% - 50%, and 60% - 60% respectively. The last scenario being the third one will consist of 1 thruster generator and 1 main diesel generator with 2 motors also being the load. The loads will be 75% - 75%, 80% - 80%, and 85% - 85%, to summarize it can be seen on Table 1. From the scenario the result voltage and current will be analyse according to its rules and formula.

| Scenario | Power Supply                   | Load                        | Variation                  |
|----------|--------------------------------|-----------------------------|----------------------------|
| 1        | 2 Thruster Generator           | 2 Bow Thrusters             | 60%-75%                   |
|          |                                |                             | 100%-80%                  |
|          |                                |                             | 100%-100%                 |
|          |                                |                             | 110%-110%                 |
| 2        | 1 Thruster Generator           | 2 Bow Thrusters             | 40%-40%                   |
|          |                                |                             | 50%-50%                   |
|          |                                |                             | 60%-60%                   |
| 3        | 1 Thruster Generator and 1 Diesel Generator | 2 Bow Thrusters and ship load | 75%-75%                   |
|          |                                |                             | 80%-80%                   |
|          |                                |                             | 85%-85%                   |

2.5 Sinusoidal Wave and Phasor Diagram

After the current and voltage are measured on the system, the sinusoidal wave of the voltage is also monitored using an oscilloscope to see the angles of each voltage varies. After the sinusoidal wave are recorded, the wave is then redrawn on excel and the phasor diagram are made to see the vector of the voltages.

3. Results and Discussions

The result of this analysis will show how much of an unbalance occur on each of the scenarios, comparing and calculating it to the standard based on the definitions of unbalance.

3.1 1st Scenario

On the first scenario there are 4 variety of variation which are 60% - 75%, 100% - 80%, 100% - 100%, and 110% - 110% load. The variations are how much load of its initial maximum value of the motors that are used as the bow thrusters.
1st Variation. The first variation gave a result of $LVUR$, $PVUR$, and $VUF$ with a value of 0.35%, 0.61%, and 3.09% for the first generator and 0.44%, 0.77% and 2.94% for the second generator. The value that were obtained have some that passing the limit of unbalance, and that is the $PVUR$ of the first and second generator with the value of 0.77% and 0.61% which the limit is 0.5%. The result of the voltages is $220\angle 0^\circ$, $218\angle -113.7^\circ$, and $218\angle 123.18^\circ$. The sinusoidal wave and phasor diagram of the 1st variation can be seen on Figures 2 and 3.

2nd Variation. On the second variation the result for $LVUR$, $PVUR$ and $VUF$ are 0.18%, 0.62%, and 3.09% for the first generator and 0.44%, 0.47%, and 3.23% on the second generator. Disturbance only happened on the first generator that the value of the $PVUR$ is 0.62%. The value of the voltage for the second variation with its angle are $217\angle 0^\circ$, $215\angle -113.7^\circ$, and $215\angle 123.18^\circ$. The sinusoidal wave and phasor diagram could be seen on Figures 4 and 5.

3rd Variation. The third variation results in the value of $LVUR$, $PVUR$ and $VUF$ are at 0.45%, 0.62% and 3.08% for the first generator and 0.72%, 0.78% and 2.78% for the second generator. An unbalance that the value is more than the standard is the $PVUR$ with the value of 0.62% on the first generator and 0.78% on the second generator.

The reason behind this is because the high excessive of neutral current thus making losses that cause disturbance to the voltage. The result for the result with its angle in this variation are $215\angle 0^\circ$, $213\angle -113.7^\circ$, and $213\angle 123.18^\circ$. The result for the sinusoidal wave and phasor diagram are shown on Figures 6 and 7.
4th Variation. For the fourth scenario with the load being 110%, motors could not work with load thus making no result for this variation.

3.2 2nd Scenario

The second scenario only uses one thruster generator while powering two motor thrusters. The load for these scenarios is 40% - 40%, 50% - 50% and 60% - 60%.

1st Variation. The result for scenario 2 for the LVUR, PVUR, and VUF are 0.17%, 0.61% and 0.31%. Based on the result the PVUR are the one with the result being more than the limit of 0.5%. The result for the voltage of this variation are 220∠0°, 220∠-120°, and 218∠120°. The sinusoidal wave and the phasor diagram of variation can see on Figures 8 and 9.

![Figure 8. Sinusoidal wave for scenario 2 variation 1](image1)
![Figure 9. Phasor diagram for scenario 2 variation 1](image2)

2nd Variation. The result for the second scenario for the LVUR, PVUR and VUF are 0.61%, 0.30% and 3.14%. On this variation no result gave a value more than the limit of each of their definitions thus having an allowable unbalance voltage condition. The value of the voltages are 220∠0°, 219∠-126.5°, and 220∠116.76°. For the sinusoidal wave and the phasor diagram can be seen on Figures 10 and 11.

![Figure 10. Sinusoidal wave for scenario 2 variation 3](image3)
![Figure 11. Phasor diagram for scenario 2 variation 2](image4)

3rd Variation. The third scenario being with a load of 60% - 60%, have a result for its LVUR, PVUR and VUF at the value of 0.35%, 0.30% and 3.30%. On this scenario no result from the definition calculation gave a result more than the limit of each definition. The value of the voltages are 220∠0°, 220∠-123.2°, and 219∠113.7°. The sinusoidal wave and phasor diagram for scenario 2 variation 3 can be seen on Figures 12 and 13.
3.3 3rd Scenario

The third scenario being the last scenario comes with the power supply being 1 diesel generator and 1 thruster generator. On this scenario there are also load that are assumed as the ship load being a 480W total load in form of lamps. The assumed ship load will be the same on each of the variations. The scenario has 3 variation which are 75% - 75%, 80% - 80% and 85% - 85% on the motor thruster load.

1st Variation. The first variation gives result of LVUR, PVUR and VUF at a value of 0.33%, 0.30% and 0.15% for the diesel generator and 0.42%, 0.46% and 0.26% for the thruster generator. The result from the calculation are all still below the threshold of each definition.

The value of current on the neutral line on both generators are relatively high with the value of 4.11 A and 2.9 A. The result for the voltages is $219\angle 0^\circ$, $220\angle -120^\circ$, and $220\angle 120^\circ$. Also, from the angle value that phase angle difference are 120° apart. Sinusoidal wave and phasor diagram of variation 1 can be seen on Figures 14 and 15.

2nd Variation. The second variation of the third scenario have the result for LVUR, PVUR and VUF at 0.16%, 0.30% and 3.30% for the diesel generator and 0.41%, 0.30% and 3.08% for the thruster generator. On this variation none of the result have its value higher than their respective definition standard.
Although the same as the 1st variation the current on the neutral line are also high at a value of 3.6 A for the first generator and 2.87 A for the second generator. The result of voltage for this variation are $220\angle 0^\circ$, $220\angle -123.2^\circ$, and $219\angle 113.7^\circ$. The difference between this scenario and the previous scenario is that even though the current are at a lower value the angles of the voltage are shifted. The sinusoidal wave and phasor diagram can be seen on Figures 16 and 17.

3rd Variation. The last variation which is the third variation of scenario 3 with the load being 85%-85%. The LVUR, PVUR and VUF are 0.33%, 0.61% and 3.09% for the first generator and 0.58%, 0.31% and 3.30% for the second generator. On this variation, from the definition its value is higher than the limit is the PVUR with 0.61%. The result for this scenario is $221\angle 0^\circ$, $219\angle -123.2^\circ$, and $219\angle 113.7^\circ$. The sinusoidal wave and phasor diagram can be seen on Figures 18 and 19.

4. Conclusions
Based on the results that were obtained from measuring the units and also calculating them, it is found that the values are almost all passable in term of each definition. From the result the PVUR or phase voltage unbalance rate is the most dominant as indicated by its higher value than the limit. This is due to an unbalance that happens on the system which can be figured out by looking at the high amount of neutral current at a certain scenario and/or variation.

A relay is also possible to be installed, named phase balance relay that will trip the equipment in case an excessive unbalance happened. Further, a compensator is usually use. A compensator has both reactor and capacitor in case the voltage is too inductive and reactive.
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