A Study of the Method for Calculating the Optimal Generator Capacity of a Ship Based on LNG Carrier Operation Data

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Abstract: Currently, the total generator capacity installed in most ships is greater than the required capacity. In addition, due to new environmental regulations, various auxiliary gears are required to avoid breaking the law. Therefore, the internal environments of ships, such as their machine rooms, have become narrower, making creating space more important than ever before. This paper provides a method for optimizing generator capacity through an analysis of total load data in order to avoid overestimating the generator capacity. In addition, an actual situation in which the generator capacity is determined by the number of cylinders is considered. Three practical case studies with different possible combinations of generators and varying capacities are presented. Therefore, this method can secure space and reduce weight, which can be beneficial in many ways. Additionally, since it does not require various types of data, this information can be used for already built ships or those that will be made in the future.

Keywords: generator capacity; heavy consumer; International Maritime Organization; total load; variation

1. Introduction

A new environmental regulation was issued by the International Maritime Organization (IMO). It applies not only to new ships but also to existing ships, and reduces the global limit of sulfur dioxide (SOx) from 3.5% to 0.5%. It took effect on 1 January 2020 [1]; as a result, many kinds of systems for reducing emissions or saving energy, such as filters for SOx or energy storage systems (ESSs), began to be installed [2]. Along with ESSs, electric propulsion ships are being actively researched and developed [3]. The purpose of most ships is to carry goods, people, or luggage. For this reason, the spaces, such as the deckhouse, machine room, and cabin, are built using as little volume as possible. The builders of future ships can prepare for this regulation, but it is a critical issue for ships that have already been built and are transporting or working. Ships that are already sailing need additional equipment to reduce SOx in the existing facilities, so their engine rooms will become narrower and their weight will significantly increase. This causes economic losses for shipowners. In addition, if some machinery is to be additionally installed in or removed from a ship that has already been built, the shipowner has to pay a large cost because they must install or remove the outer periphery of the machine room depending on the size of the machinery. In addition, ships cannot operate while staying at shipyards, resulting in economic losses. Therefore, it is necessary to be cautious when inserting and disassembling devices. Ships are classified according to their displacement and usage, rather than with fixed models like cars, and each ship has its own unique properties, so each ship has its own name.

Various data are measured on a ship, and those data belong to the shipowners. The data are linked to the route of a ship, which is directly connected to the competition between shipowners. Therefore, it is close to impossible to share data with shipyards.
because shipyards deal with multiple shipowners as customers. In addition, for the same reason, the names of shipyards and shipowners cannot be published. The existing calculation method involves finding the generator capacity where the maximum load is 80% to 90% of the total generator capacity. It overlooks the optimization of the generator capacity by overestimating the capacity for safety reasons. As technology has advanced, ship power system equipment has become more secure. Accordingly, shipyards have made special contracts with shipowners to calculate generator capacities and to perform research with actual total load data collected from target ships.

The target ship of this paper is a liquefied natural gas (LNG) carrier, which is a gas carrier in the general commercial ship category. Therefore, unlike in the conditioner ships that are usually considered, there are devices called heavy consumers inside this ship, and the types are a high-duty compressor (HDc), low-duty compressor (LDc), and single mixed refrigerant (SMRc) [4,5]. They are called heavy consumers because they consume a lot of power during operation. The LDc and HDc consume up to 700 kW, and each ship is equipped with two of each; the SMRc also consumes up to 1500 kW. Figure 1 shows the typical power system of an LNG carrier, where G stands for generator, E stands for engine, C stands for compressor, and P stands for pump. The power system of a ship has a short distance over which there is no energy loss due to transmission [6,7]. Therefore, the total load is the same as the total amount of power used. In addition, the ship has a total of four units of generators; the generator capacities of two of them are 3220 kW, and those of the others are 2760 kW. The number of cylinders installed for a large generator is seven, and a small generator has five; one of these cylinders can generate 460 kW. The distribution system for each ship is symmetrical, and the number of generators ranges mostly from 3 to 5 [8–10], but the types and sizes of many other devices that depend on them vary from ship to ship.

**Figure 1.** Example of a typical power system of a liquefied natural gas (LNG) carrier.
A generator contains an engine that is assembled with several units of cylinders for power generation. A generator and its engine have a lifespan of about 30 years. A generator’s capacity changes according to the number of cylinders in the engine, and the generating capacities of the cylinders differ in size for each company and model. In the case of medium-sized or large-sized ships—like the target ship in this paper—most use a capacity of 300 to 500 kW per cylinder and consist of 4 to 10 cylinders per generator. In addition, all data are displayed on an instrument panel installed in the captain’s room, and the types of data that are recorded depend on the equipment. For load data, there is a meter installed in each generator.

The data used in this paper consist of 16 days of primary test sailing data and about 3 months of actual sailing data gathered from a task from shipyard “A”. The 16 days of primary test sailing data included the total load, the revolutions per minute (rpm) of the propulsion engine, speed, and the load of the heavy consumers per minute. However, it is not allowed to publicly publish these data, so they have been reformed and scaled. Moreover, from the 16 days of primary test sailing data, schedule data were also obtained, and in the results of the analysis, there was no correlation between the total load and the speed, which meant that the total load was unpredictable. The 3 months of actual data only contain the total load data per minute. It is also not allowed to publish these data, so the actual sailing data for about 3 months were compressed, reformed, and scaled to 1 month with the same waveform. For the shipyard, it is necessary to treat the property of the total load data of the ship as unpredictable. Since the load data could not be predicted, the reflected variation value was calculated using the variation to obtain a value that can increase safety. In addition, after analyzing the load data, a value was derived through polynomial curve fitting (PCF). The reflected variation value was added to obtain the ideal generator capacity. In this paper, the fact that the generator capacity changes according to the number of cylinders was considered. Generator capacities were selected and combined to represent a case study, and the optimized total generator capacity was derived through comparison and analysis with the original case.

The structure of this paper is as follows. Section 2 introduces the mathematical tools used for calculating a PCF value and confirms the unpredictability of the total load compared with the speed of the ship. Then, the reserve power and spinning reserve power are presented, and its rate is analyzed using actual sailing data. After that, the optimized value is calculated using the variation. In Section 3, based on the optimized values, virtual scenarios for case studies 1 to 3 are created and compared with the original data to confirm their suitability.

2. Materials and Methods

Figure 2 shows the materials and methods used in this paper to obtain the optimal generator capacity. The red-colored box in Figure 2 contains the process of analysis of the total load data. The blue-colored box in Figure 2 shows the process of calculating the PCF value. However, there are some problems with directly using the PCF value; for example, a generator’s capacity depends on the cylinder units, which makes it difficult to produce the same capacity as the PCF value. Therefore, it is necessary to find the value of the margin from the total load data analyzed, and the solution for finding the value of the margin—the reflected variation value—is found in Section 2.5.
2.1. Mathematical Tools

2.1.1. PCF and Root Mean Square Error (RMSE)

The PCF returns the optimal coefficient \( (p_n) \) to form an optimal line for the data \( (p(x)) \) from the least-squares view. Therefore, by using PCF, one can find the optimal line for all the data using Equation (1), where \( x \) is the data of the total load and numbers of all the data are \( n \).

\[
p(x) = p_1x^n + p_2x^{n-1} + \ldots + p_nx + p_{n+1}
\]  

(1)

The RMSE equation is widely used to check the error rate of a corresponding value, and in this paper, the RMSE is used to secondarily confirm the value generated through PCF. \( y_i \) stands for the total load of each datum, and \( \hat{y}_i \) stands for the PCF values from PCF. For all data, the difference between \( \hat{y}_i \) and \( y_i \) is calculated and then squared to obtain the average value. The RMSE value is obtained when the root of the obtained value is squared. The RMSE value is calculated and presented in the same manner by adding and subtracting specific numbers from \( \hat{y}_i \) to prove that the result of PCF is an optimized value. Equation (2) shows the RMSE equation.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}}
\]  

(2)

2.1.2. Variation

The variation represents the greatest positive difference from the last minute within a certain time. For example, based on the ten-minute variation, the total load value representing the maximum for 10 min is calculated for every minute. Subtracting from the total load corresponding to the standard time gives the corresponding rate of change, and the rate of change is calculated for all data.

\[
A \text{ value of # minute variation} = \text{maximum total load data in (} A_1, A_2, A_3, \ldots A_{10} \text{)} - A_1
\]  

(3)

These values were separated by 100 kW. In addition, when \( A_1 \) is the maximum in a 10 min period, the variation value is negative or 0. These are treated as the same result because the same result is obtained in the analysis.

Figure 2. Data analysis.
2.1.3. Generator Capacity Selection Index (GCSI)

After completing the analysis, this paper proposes the GCSI method as a mathematical model that can be used to find out which generator capacity is the most optimal by comparing case studies. The GCSI is used to calculate the average reserve rate \( R_{\text{avg}} \), safety index \( S \), and experience index \( k \) for the case study and the original case. The \( S \) stands for the frequency of exceeding the largest generator’s capacity. This value will show through practical consideration in the result part. The \( k \) is a selected value by the engineer of shipyard. The engineer considered generator capacity that has been built on ships for decades which is 0.001. Equation (4) shows how the reserve rate value is obtained. The safety index is the frequency with which the large generator’s capacity is exceeded in each case. Equation (5) shows the GCSI \( (P) \) method.

\[
R = \frac{\text{Total load}}{\text{The total generator capacity in operation}} \times 100
\]

\[
P = R_{\text{avg}} + S \times k
\]

When applying Equation (4) to find the optimized capacity among the different case studies \( (n) \), the optimized generator capacity is set as \( (GC) \) and the minimum value among the cases is found through Equation (6).

\[
GC = \min\left( P_1\left(R_{\text{avg}}, S_1\right), P_2\left(R_{\text{avg}}, S_2\right), P_3\left(R_{\text{avg}}, S_3\right), \ldots, P_n\left(R_{\text{avg}}, S_n\right) \right)
\]

2.2. Analysis of Test Sailing Data

The data in Figure 3 are reformatted and scaled from the primary test sailing data; these are important in proving that the load data of the ship are not correlated with its speed. Figure 3 shows the relationship between the load and speed. From 0 to 10 h, the total load of the ship is around 2700 kW. At the same time, the speed of the ship begins at approximately 10 Knots, rises to 15 Knots, and then declines to 14 Knots. After 10 h, the total load decreases, but the speed increases. Since the speed shows increases and decreases when the total load has not increased or decreased, the total load and the speed are not correlated.

![Figure 3. Example of the test sailing data with the total load and speed.](image-url)
2.3. Analysis of Actual Sailing Data

In Figure 4, the black-colored line represents the total load, and the brown line represents the total generator capacity in operation. The cyan-colored line shows the total generator capacity overall, which is 11,040 kW. The brown-colored arrow indicates spinning reserve power, and the cyan-colored arrow indicates reserve power. In Figure 4, the total load shows a certain range, while the brown line is not constant. This is to change the generator in consideration of the wear of the cylinder in the generator. The generator is composed of cylinders. If one generator operates for a long period, the wear of the cylinder will be significant compared to other generators. Therefore, there may be situations where you need to replace that generator. To replace large equipment such as generators, ships require large costs to make holes from the outer shell of the ship to the generator. Therefore, for shipowners, the wear of the cylinder in the generator is one of the important management matters.

Figure 4. Reserve power and reserve rate of the ship.

From day 0 to around day 6, the total load is mostly 2000 kW, and these days are estimated to be when heavy fuel oil (HFO) is used for fuel. After around day 6, the total load is shown to mostly be around 2700 kW, and those days are estimated to be when LNG is used for fuel. This is because when an LNG carrier uses LNG for fuel, the LDc provides LNG to the generators or main engines, which incur about up to 700 kW of load—the value of one heavy consumer in an LNG carrier.

In addition, this shows that the total load is not constant, and the peak rises. Of the equipment built into the ship, there are some machines that use a lot of electricity, and the peak rises when they are used, as shown in the graph. For example, the peak seen around day 14 is the port discharge, which is when LNG is unloaded from the ship to the port. This is the point in the sailing schedule where the LNG carrier uses the most electricity, that is, 8327 kW. At this time, since the LNG is pushing LNG from the inside of the ship to the shore, many cargo pumps are used, and about 500 kW of power is used per unit. In addition, days 2, 5, 6, 19, and 25 show peaks. This is because an SMRc is running, which consumes up to 1500 kW of electricity.

Table 1 shows the numerical values of the spinning reserve power and reserve rate. The minimum reserve power is 507.70 kW and its rate is 15.77%. Unlike the land power system, the ship has only four generators, which means that the choice is narrow. Therefore, this minimum result is reasonable. The maximum power is shown to be 8464.82 kW, and its rate is 76.67% before day 23. The spinning reserve power line peak rises intermittently in the middle. This indicates an increase in the spinning reserve power for a short time after
inserting a new generator to change it depending on its wear and turning off the existing generator. However, the average spinning reserve power is 2465 kW and its rate is 44.22%. This amount is the capacity of a small generator, which is 2300 kW.

Table 1. Original spinning reserve power and its rate.

| Type                      | Minimum | Maximum | Average |
|---------------------------|---------|---------|---------|
| Spinning reserve power (kW) | 507.70  | 8464.82 | 2465.27 |
| Spinning reserve rate (%)  | 15.77   | 76.67   | 44.22   |

2.4. Excluding Data for Analysis

Figure 5 shows the typical power management system (PMS) of an LNG carrier. When heavy consumers, such as an SMRc compressor or cargo pumps, are operating, the PMS of a ship requires at least two operating generators. Therefore, the peaks that indicate the use of heavy consumers should be excluded from the analysis. These sections are marked with red circles in Figure 4. In addition, the blue circle in Figure 4 has less load than most of the total load value over the entire period. Thus, it is assumed to be in the HFO mode, and this becomes noise data when obtaining the PCF value line because the total load is always less than one large generator’s capacity. Therefore, the data in the blue circles should also be excluded. The number 0.9 in the decision symbol on the right side of Figure 5 indicates 90% of the generator capacity, which is set by the PMS to prevent blackouts in the ship’s power system. Therefore, when the power usage exceeds 90% of the generator capacity in operation, an additional generator is turned on.

![Figure 5. Typical power management system of an LNG carrier.](image_url)

The black line in Figure 6 shows the total load data after excluding the heavy consumer peaks and the low total data, which are indicated by the red circles and the blue circle in Figure 4, respectively. The red line shows the PCF value, which is 2647 kW. Since there are no heavy consumers or low total load periods, the optimal line value can be used to calculate the generator capacity.
Figure 6. Total load graph excluding the low total load data.

Table 2 shows the RMSE of the PCF value from Figure 6 to confirm if it is the PCF value by subtracting 20, 40, and 60 kW from the original PCF value. The original PCF value shows the smallest RMSE (89.249) compared to the other values, whether subtracted and added; thus, it is confirmed that the PCF value is 2647 kW and is suitable as the representative value for calculating the generator capacity.

Table 2. Root mean square error (RMSE) values excluding the heavy consumers.

| Type (kW) | −60   | −40   | −20   | Original | +20   | +40   | +60   |
|----------|-------|-------|-------|----------|-------|-------|-------|
| RMSE     | 2587  | 2607  | 2627  | 2647     | 2667  | 2687  | 2707  |
|          | 107.546 | 97.806 | 91.464 | 89.249   | 91.461 | 97.800 | 107.538 |

2.5. Variation

The load data of a ship are unpredictable, and it is very hard to collect other types of data, such as the load data of heavy consumers, the rpm of a generator or main engine, or the wind and weather. Therefore, the variation and its rate can be used to determine the operation or dropout of a generator by obtaining the reflected variation value [11].

In this section, a variation of 5, 10, or 15 min is chosen to calculate the generator capacity. As shown in Figure 5, when a generator starts to operate and connects to the power system of a ship, it generally needs 10 to 15 min to be ready and connected. The target ship’s PMS requires at least 10 min before it is ready. Therefore, the ten-minute variation data are considered.

2.5.1. Ten-Minute Variation

Figure 7 shows the ten-minute variation of a histogram. The range from the negative values to 0 kW shows 2634 counts, making up 10.06% of the rate, and the range from 0 to 100 kW shows 18,055 counts, making up 68.97% of the rate. In addition, the range from 100 to 200 kW shows 16.63%, and the range from 200 to 300 kW shows 3.85%. The variation from 300 to 400 kW shows 127 counts, making up 0.49% of the rate, and over 400 kW, 0 counts are shown.
2.5.2. Overall Variation

Table 3 shows 1, 5, 10, and 15 min of variation and the rates thereof. All variations after the 400 kW range show 0 counts. Therefore, the reflected variation value is up to 400 kW when calculating the capacity of the generator.

Table 3. Results of the 1, 5, 10, and 15 min variation.

| Range (kW) | 1 min | 5 min | 10 min | 15 min |
|------------|-------|-------|--------|--------|
|            | Count | Rate (%) | Count | Rate (%) | Count | Rate (%) | Count | Rate (%) |
| (<999)--0 | 13,214 | 13,214 | 50.46 | 13,214 | 20.25 | 13,214 | 10.06 | 13,214 |
| 1--99     | 11,300 | 11,300 | 43.15 | 11,300 | 64.60 | 11,300 | 68.97 | 11,300 |
| 100--199  | 1407  | 1407  | 5.37 | 1407  | 12.26 | 1407  | 16.63 | 1407  |
| 200--299  | 243   | 243   | 0.93 | 243   | 2.59 | 243   | 3.85 | 243   |
| 300--399  | 21    | 21    | 0.08 | 21    | 0.30 | 21    | 0.49 | 21    |
| 400--499  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |
| 500--599  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |
| 600--699  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |
| 700--799  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |
| 800--899  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |
| 900--999  | 0     | 0     | 0.00 | 0     | 0.00 | 0     | 0.00 | 0     |

The PCF value from Section 2.4 is 2647 kW, and the highest reflected variation value from Table 3 is 400 kW. To choose the representative value, the PCF value and reflected variation value should be added, which amounts to 3047 kW.

3. Case Studies and Results

The PCF value from Section 2.4 is 2647 kW, and the highest reflected variation value is 400 kW. Therefore, the representative capacity of the generator is 3047 kW, which is shown with the red-colored line in Figure 8. Figure 8 also shows the possible generator selection. The green-colored line is for a 3680 kW generator that has a total of eight cylinders. The magenta-colored line is a 3220 kW generator that has a total of seven cylinders. The blue-colored line is a 2760 kW generator that has a total of six cylinders. If a generator’s capacity is less than 2760 kW, at least two generators will always be needed to operate. Therefore, 2760 kW is the minimum selection for the large generator.
Each generator’s capacity.

The values to be considered in calculating the total capacity are the number of generators and the capacity of each generator. In Section 2.3, the highest load was shown to be 8327 kW, which means that the reserve power is 2713 kW. Therefore, if the total capacity of the generator is higher than 8327 kW, then it is safe for any situation. Furthermore, 2713 kW indicates the total generator capacity. This is larger than the small generator capacity which is 2300 kW. Therefore, the number of generators can be operated with three units instead of the existing four units. Otherwise, each of the four generators can reduce the units of the cylinder. However, it is more advantageous to reduce the number of generator units from 4 to 3 rather than reducing the number of cylinders for four generators in securing space in the ship’s machine room. However, for securing space in the ship’s machine room, it is more advantageous to reduce the number of generator units rather than reducing the number of cylinders.

Therefore, in the case studies, each of the generator capacities was selected according to the numbers of cylinders that would be considered in reality. In addition, a total of three generator combinations were denoted as Cases 1–3, and they are listed in Table 4. The results of each case study are compared with the spinning reserve power of the original case and those of Cases 1–3. The reasoning behind comparing the spinning reserve power is to see the efficiency of each case. The safeness of each case is also compared to see if the results can be considered from a practical perspective.

Table 4. Generator combinations for each case.

| Case  | Number of generators | Total power of generators | Total |
|-------|----------------------|---------------------------|-------|
| 1     | 2                    | 5520 kW                   | 9200 kW |
|       |                      | 3680 kW                   |       |
| 2     | 2                    | 6440 kW                   | 8740 kW |
|       |                      | 2300 kW                   |       |
| 3     | 2                    | 7360 kW                   | 9660 kW |
|       |                      | 2300 kW                   |       |

3.1. Case 1

The combination of generators in Case 1 involves a total of three generators. The selected generator capacities are two 2760 kW generators and two 1840 kW generators. The reduction in the cylinders of the original small generator is because of the total capacity.
If this combination would have two 2300 kW generators instead of 1840 kW generators, then the total capacity would be 10,120 kW. This is larger than the original total capacity. In addition, if one of the 2300 kW generators was reduced, then the total capacity would be 7820 kW, which is smaller than the highest load. According to Figure 4, from the beginning to around day 7, the PMS requires at least two generators because the load values are over 2760 kW, which will cause large amounts of reserve power to be generated.

The blue-colored line in Figure 9 shows the spinning reserve power for Case 1. The blue line is compared with the original spinning reserve power. The spinning reserve power of Case 1 comes close to the total load data, which means that the spinning reserve power is reduced. However, from around day 7 to around day 14, the spinning reserve power shows a much higher total load than on other days. This is because the total load exceeds the capacity of a large generator, so another generator turns on to make up for the difference.

Figure 9. Spinning reserve power of all cases and original case.

3.2. Case 2

The combination of generators in Case 2 comprises a total of three generators. The selected generator capacities are two 3220 kW generators and a 2300 kW generator. This combination can handle the highest load because the total capacity is 8740 kW, which is 413 kW larger than the maximum; as shown in Figure 9, all of the load data are under 3220 kW, which is reliable.

The magenta-colored line in Figure 9 shows the spinning reserve power for Case 2. Compared with the original spinning reserve power, the spinning reserve power of Case 2 comes closer to the total load data. In addition, compared with the results of Case 1, the peak of the magenta-colored line rises only when necessary. Moreover, the total capacity of the generator is less than in Case 1. Therefore, the highest peak at around day 14 is closer to the total than that of Case 1. Each capacity of the generator is larger than in Case 1. However, the peak of Case 2 from around day 7 to day 14 is less than that of Case 1. This is because the large generator in Case 2 has enough capacity for that period’s total load.

3.3. Case 3

The combination of generators in Case 3 comprises a total of three generators. The selected generator capacities were two 3680 kW generators and a 2300 kW generator. This combination can handle the greatest load because the total capacity is 9660 kW, which is 1333 kW greater than the maximum load. According to Figure 8, all of the load data are under 3680 kW, which is reliable.
The green-colored line in Figure 9 shows the spinning reserve power for Case 3. Compared with the original spinning reserve power, most of the spinning reserve power of Case 3 comes closer to the total load data. The reason that some periods have a higher spinning reserve power than the original spinning reserve power is that the large generator in Case 3 has a larger capacity than the original large generator. Therefore, in the situation of the operation of one generator, Case 3 shows a higher spinning reserve power than the original spinning reserve power. Compared with the results of Cases 1 and 2, there are fewer rising peaks of the green-colored line than for the previous cases. Around day 1 and right after day 5, the peaks in the low total load period are lower than the large capacity of the generator. Therefore, no more than one large generator is needed. Moreover, since the period needs only one generator, the spinning reserve power of Case 3 is higher than that of Cases 1 and 2.

3.4. Results

Table 5 shows the overall spinning reserve power and the rates of the original case and Cases 1–3. The lowest result for the minimum spinning reserve power is that of Case 2, which is 504.23 kW lower than the original minimum spinning reserve power. The lowest result for the maximum spinning reserve power is that of Case 1, which is 5839.86 kW lower than the original maximum spinning reserve power. The lowest average result for the spinning reserve power is that of Case 1, which is 1631.69 kW lower than the average of the original spinning reserve power.

Table 5. Overall results for the spinning reserve power and rate.

|                     | Original          | Case 1            | Case 2            | Case 3            |
|---------------------|-------------------|-------------------|-------------------|-------------------|
| Spinning reserve    | Minimum           | Maximum           | Average           | Minimum           | Maximum           | Average           |
| power (kW)          | 507.70            | 8464.82           | 2465.27           | 6.70              | 2624.96           | 833.58            |
| Spinning reserve    | 15.77             | 76.67             | 44.22             | 0.10              | 57.06             | 20.57             |
| rate (%)            |                   |                   |                   |                   |                   |                   |

Table 6 shows the practical safeness of each case. The first row shows the results when the capacity of the large generator is close to the PCF value. This is important because the efficiency decreases as the capacity of the generator moves away from the PCF value line, which represents the optimal efficiency. Case 2 shows the closest capacity of the generator, and Case 3 shows the farthest capacity of the generator. The second row shows how frequently each case exceeds the capacity of the large generator over the entire time period, which includes the red and blue circle periods in Figure 4. This frequency can cause a ship to be threatened with blackouts, so it is advantageous to have as few cases as possible in order to be on the stable side. However, this must be considered carefully because a lower chance of exceeding the capacity means a lower efficiency. The worst case is Case 1, in which the capacity is exceeded 1332 times. This means that there are many times when another generator needs to be turned on for just a little more electricity. Cases 2 and 3 show a frequency of 0, so Cases 2 and 3 have the same safeness.

Table 6.

|                     | Original          | Case 1            | Case 2            | Case 3            |
|---------------------|-------------------|-------------------|-------------------|-------------------|
| Spinning reserve    | Minimum           | Maximum           | Average           | Minimum           | Maximum           | Average           |
| power (kW)          | 3.47              | 2864.74           | 893.82            | 13.40             | 3399.86           | 1295.11           |
| Spinning reserve    | 0.10              | 51.90             | 23.39             | 0.22              | 56.85             | 31.30             |
| rate (%)            |                   |                   |                   |                   |                   |                   |
Table 6. Checklist for practical consideration.

| Is the large generator’s capacity close to the PCF value? (difference from the PCF value) | Case 1 | Case 2 | Case 3 |
|---------------------------------------------|--------|--------|--------|
| Frequency of exceeding the large generator’s capacity (safety index) | A little far (−287 kW) | Close (+173 kW) | Far (+633 kW) |
| Frequency of exceeding the large generator’s capacity (safety index) | 1331 | 0 | 0 |

Overall, Cases 1 to 3 show better results for the spinning reserve power and its rate than the original data. The best choice for safety is either Case 2 or Case 3, both of which have 0 total loads that exceed the capacity of the large generator. The most efficient choice is Case 1, which has the lowest average reserve power. However, in Case 1, the total load is very close to the capacity of the generator for a long time, so there is a high safety risk. Case 3 shows the farthest value from the PCF value, which means that Case 2 is a better choice than Case 3. Moreover, Case 2 is closest to the PCF value, which means that it is the best in terms of efficiency and safety. The safeness of Case 2 and the original data are similar because they use the same generator capacity for the large generator. However, the efficiency of Case 2 is much better than that of the original data, as seen in Table 5. As seen in Table 7, the GCSI value of Case 2 is 23.39, which is the minimum value in all cases. Therefore, Case 2 has the optimal generator capacity. It operates with a total of three units of generators by removing a 2300 kW generator from the four original generator units.

Table 7. Generator capacity selection index (GCSI) value of each case.

| Original Case | Case 1 | Case 2 | Case 3 |
|---------------|--------|--------|--------|
| GCSI Value    | 57.75  | 33.88  | 23.39  | 31.3   |

4. Conclusions

In this paper, the total load data were analyzed by excluding interfering data. With the total load data analyzed, the PCF value was obtained through PCF. After that, the PCF value was added to the most suitable reflected variation value, which was obtained through variation analysis. Case studies were practically applied; the capacity of a cylinder was set to 460 kW and the generators’ capacities were selected and composed accordingly. In addition, the case studies were analyzed and compared with the original case using the GCSI method to figure out which case’s generator combination had the most optimal generator capacity. According to GCSI results, it was concluded that Case 2 was the most suitable in terms of safety and efficiency; it was possible to replace the four existing generators with three units of generators in Case 2. Therefore, if Case 2 is applied, space can be secured in the machine room, so more equipment can be installed—such as for reducing SOx emissions—and more cargo can be loaded. Furthermore, the energy efficiency can also be increased by applying a lower reserve ratio than that of the original case to cover the highest total load.

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