Generator Capacity Sizing

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1. Introduction

The selection of the number of generator sets and the power rating of each generator set depends on a number of factors; usually, the objective is to minimize life cycle cost while meeting all regulations, adhering to class society rules, and providing sufficient capacity for future loads. In the United States, 46 CFR 111.10 states the following power requirements for generating sources:

> "(a) The aggregate capacity of the electric ship's service generating sources required in § 111.10-3 must be sufficient for the ship's service loads.
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> (b) With the ship's service generating source of the largest capacity stopped, the combined capacity of the remaining electric ship's service generating source or sources must be sufficient to supply those services necessary to provide normal operational conditions of propulsion and safety, and minimum comfortable conditions of habitability. Habitability services include cooking, heating, air conditioning (where installed), domestic refrigeration, mechanical ventilation, sanitation, and fresh water.
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> (c) The capacity of the ship's service generating sources must be sufficient for supplying the ship's service loads without the use of a generating source which is dependent upon the speed or direction of the main propelling engines or shafting.
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> (d) Operating generators must provide a continuous and uninterrupted source of power for the ship's service load under normal operational conditions. Any vessel speed change or throttle movement must not cause a ship's service load power interruption.
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> (e) Vessels with electric propulsion that have two or more constant-voltage generators which supply both ship's service and propulsion power do not need additional ship's service generators provided that with any one propulsion/ship's service generator out of service the capacity of the remaining generator(s) is sufficient for the electrical loads necessary to provide normal operational conditions of propulsion and safety, and minimum comfortable conditions of habitability.
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> (f) A generator driven by a main propulsion unit (such as a shaft generator) which is capable of providing electrical power continuously, regardless of the speed and direction of the propulsion shaft, may be considered one of the ship's service generating sets required by § 111.10-3. A main-engine-dependent generator which

is not capable of providing continuous electrical power may be utilized as a supplemental generator provided that a required ship's service generator or generators having sufficient capacity to supply the ship's service loads can be automatically brought on line prior to the main-engine-dependent generator tripping off-line due to a change in the speed or direction of the main propulsion unit."

ABS MVR requires the following:

"3.1 Number and Capacity of Generators

3.1.1 General (2020)

The number and capacity of generating sets is to be sufficient under normal seagoing conditions with any one generator in reserve to carry:

● Those electrical loads for essential services and for minimum comfortable conditions of habitability, as defined in 4-8-1/7.3.3 and 4-8-1/7.3.4, as applicable and

● The electrical loads related to the electric power critical notations listed in 4-8-1/7.3.6.

In addition, where electrical power is necessary to restore propulsion, the capacity is to be sufficient to restore propulsion to the vessel in conjunction with other machinery, as appropriate, from a dead ship condition within thirty minutes, as defined in 4-1-1/1.9.6. See also 4-8-2/3.1.3.

For vessels of 500 GT and above, where the main source of electrical power is necessary for propulsion and steering of the vessel, the system is to be so arranged so that, in the event of the loss of any one of the generators in service, the electrical supply to equipment necessary for propulsion and steering and to provide safety of the vessel will be maintained or restored in accordance with the provision in 4-8-2/3.11.2 or 4-8-2/3.11.3."

IEEE Std 45.1 recommends:

"**7.1.1 General recommendations**

For any ship operating condition, 95% of the total power generation capacity of all online generator sets and energy storage minus 95% of the rating of the largest online generator set should be greater than the sum of the online uninterruptible and short-term interruptible loads. For zonal architectures, if the power from energy storage or a generator set can serve only in-zone loads, then any energy storage or generator set power capacity in excess of the sum of that zone's uninterruptible and short-term interruptible load should not be counted in the total power generation capacity. The 95% factor is an allowance for variation in load due to equipment cycling on and off and for inaccuracies in load sharing.

7.1.2 Nonintegrated ship service power and propulsion power systems

In designs where the majority of the ship's propulsion power is not provided via the electrical power system, the loss of use of the generating unit with the highest power rating for any reason (e.g., failure, maintenance) should not impact the ability of the electrical power generation plant to supply maximum end-of-service-life ship service electric load for any ship operating condition with the remaining generators at 95% rated power.

7.1.3 Integrated power systems (IPSs)

IPSs are systems where the majority of propulsion power and ship service power are supplied from a common electrical power generating plant. The power generating plant should be designed to provide the maximum margined electric load with service life allowance (including design propulsion load) for any ship operating condition at the design rating of the generating plant. The loss of use of the generating unit with the highest power rating for any reason (e.g., failure, maintenance) should not impact the ability of the electrical power generation plant to provide the maximum of the margined electric load with service life allowance (including design propulsion load) less exempt load for any ship operating condition. Unless otherwise specified, propulsion load above the minimum of that required to achieve one half of the design speed or 7 knots (whichever is less) is exempt load. When paralleled, each generator should maintain paralleled loading within ±5% of its rated portion of the operating load. The generator sets should be designed for a 110% continuous overload rating.

Additionally, at least one of the two following criteria should be met:

- The IPS control system prevents overloading of the generators. When sufficient power is being provided to the propulsion motor(s), the IPS control system has the ability to help prevent overloading of the generators by managing the power provided to the propulsion motor(s).

- The power generating plant is designed to provide the maximum margined electric load with service life allowance (including design propulsion load) at 95% of the design rating of the generating plant."

2. Other considerations

While the rules, regulations, and guidance presented above should be met, there are other considerations that should also influence the selection of the number of generator sets and their maximum power rating.

2.1. Commonality of generator sets

To minimize operating and support costs, the number of types (generator set models) of generator sets is typically kept to 1 or 2. Each additional generator set type requires additional crew training, repair parts, and procedures. The transient performance of the different combinations of paralleled generator types should be examined to ensure compatibility.

Non-IPS ships will generally use two or more generator sets of the same generator set type. If diesel generator sets are used, two (or more) types may be employed from the same line of diesel engines. For example, generator set types using 8 cylinder and 12 cylinder diesel engines of the same series may be used; these engines should have significant parts commonality and very similar operating procedures. IPS ships are more likely to have two types of generator sets; the generator set with the larger rating may be called a “Main Turbine Generator” or MTG if gas turbine powered or “Main Diesel Generator” or MDG if diesel powered. The generator set with the smaller rating may be called a “Auxiliary Turbine Generator” or ATG if gas turbine powered or “Auxiliary Diesel Generator (ADG) if diesel powered.

2.2. Minimum loading of generator sets

The Electric Power Load Analysis (EPLA) should be used to determine both the minimum and maximum electrical load that should be supplied by the power system. The minimum electrical load should not include service life allowance (SLA) while the maximum electrical load should include SLA. One should be able to create a generator set scheduling table that covers the full range of load power from the minimum to the maximum while still meeting all electrical power system operating constraints.

When transitioning from having on line a smaller generator set to having online a larger generator set, then the maximum loading (typically 95% of the rated power) on the smaller generator set should be equal to or greater than the minimum loading (typically 20% of the rated power) of the larger generator set. For example, if one is considering an IPS configuration consisting of 2 MTGs and 2 ATGs, where the MTG rated power is 30 MW, the MTG should be operated with at least 20% of 30 MW = 6 MW of ship operating load. This implies the ATG should have a rating of at least 6 MW / 0.95 = 6.32 MW. The smaller generator set (ATG) should have a rating at least 21% of the rating of the larger generator set (MTG).

In this example, the minimum loading of a 6.32 MW generator set is 20% of its rating or 1.26 MW. If a minimum of two generator sets must be online, then the ship's operating load should be at least 2.52 MW to avoid lightly loading the ATGs.

If the lowest ship operating load is less than the combined minimum operating load of two of the smallest generator sets, one has at least three options:

- Evaluate the impact on total ownership of operating the smaller generator sets at less than the minimum loading. If the operational profile of the ship shows that the ship is expected to seldom operate at below the minimum operating load of two of the smallest generator sets, then it may prove advantageous to accept the increased maintenance cost associated with lightly loading the generator sets.
- Use an MTG with a lower rating and increase the number of ATGs with a lower rating. For example, if the MTG is reduced in rating to 27 MW and four ATGs with a rating of 2.85 MW are used (assuming the maximum ship operating load is still met), then one can transition from having 2 ATGs on line to 1 MTG without either overloading the ATGs or lightly loading the MTG. The ship's minimum operating load should be greater than 20% of 2 x 2.85 = 1.14 MW
- If allowed, use energy storage fulfilling ESM-F2 functionality with a power rating equal to the rated power of the ATG to enable operating with only one generator set online. With two ATGs installed, the combined rating of the two ATGs should be at least 21% of the rated power of the MTG. The ship's minimum operating load should be greater than 20% of the rating of a single ATG. With two 30 MW MTGs, the ATGs could have a rating of 3.2 MW and the ship's minimum operating load should be at least 0.640 MW. Energy storage is very useful in this situation.

The bottom line is that one should construct a generator set scheduling table for a proposed set of generator sets. One should verify that the generator set scheduling table does not result in generator sets being overloaded or lightly loaded. If the generator set scheduling table indicates possible underloading of generator sets, the impact of the underloading on total ownership cost should be evaluated.

2.3. Ability to evenly power main switchboards or buses.

The Electrical Power System Concept of Operations (EPS-CONOPS) may indicate certain operating conditions require the electrical power system should be operated as split plant. In split plant operation, the power system is segregated into two independent power systems. Normally, the operating load on each of the two systems will be roughly the same.

For these conditions, the EPLA should be used to determine the minimum and maximum operating load for each of the two independent power systems. For each of the two independent power systems, a generator set scheduling table should be constructed and analyzed to determine if under certain operating loads generator sets will be either lightly loaded or overloaded.

For IPS configurations, the need to support split plant usually results in an even number of MTGs and ATGs; one generator set out of service typically will not impact the ability to supply ship service loads while also supplying the minimum required propulsion load.

For non-IPS configurations to support split plant, the total number of generator sets is typically odd; with one generator set out of service, the remaining generator sets may be split evenly between the two independent systems.

The above guidance is not absolute; depending on the particular requirements and available generator set ratings, it may be possible to affordably implement an odd number of generator sets in an IPS configuration and an even number of generator sets in a non-IPS configuration.

2.4. Fault current considerations.

Traditional fault protection systems relay on the online generator sets to provide sufficient, but not too much fault current during a line-to-line short circuit. If the largest generator set has a rated power on the order of 10 times the rated power of the smallest generator set that can parallel to it, the possibility exists that the smaller generator set's fault current could be less than the rated current of the largest generator set. If this happens, it is unlikely that traditional time-current based circuit breaker coordination will be possible; more advanced fault protection techniques will have to be used.

If power is generated at high voltage and large high voltage to low voltage transformers are used to supply ship service loads, then the available fault current on the low voltage winding of the transformer may exceed the rating for commercially available circuit breakers. See Dalton (2019) for additional details. Possible solutions to this predicament include:

- Operating the power system in splint plant when the total generation capacity while operating as a single system would result in excessive fault current on the transformer secondary.
- Replace the large transformer with multiple smaller transformers. The increased impedance of the smaller transformer should result in a lower fault current.
- Replace the transformer with an isolating power electronic converter that current limits when its output is short circuited.

2.5. Dynamic response of paralleled generator sets

Different generator sets will have different dynamic responses when subjected to disturbances such as a large load tripping offline, or a bus-tie breaker tripping. In particular, the dynamic time constants of gas turbines and diesel engines can be very different. If one of the generator sets has a significantly higher rating than the other, the possibility exists that if they are originally paralleled, a disturbance could cause the smaller generator set to trip offline due to the mismatch in dynamic response. The larger generator set could then become overloaded and trip offline as well. For non-IPS ships, using multiple generator sets of the same type and rating helps prevent dynamic response issues. IPS ships usually employ at least two types of generator sets with different power ratings; a dynamic response analysis should be conducted to determine if there is a potential for a disturbance to result in a generator set tripping offline. If there is a potential problem, it may be possible to address it through advanced controls, or by employing energy storage with ESM-F4 functionality

3. Emergency generators

The emergency generator supplies power to the emergency switchboard. Normally, the rating of the emergency generator should equal the connected load of all the loads powered from the emergency switchboard; if the connected load is greater, then justification should be provided for estimating that the emergency load will be less than the rating of the emergency generator.

Some ships are allowed to use a standby generator set to serve as an emergency generator (final emergency power source); a dedicated emergency switchboard is not provided. In these systems, robust and reliable load shedding provides the highest priority to emergency loads. The standby generator should meet the requirements of an emergency generator.

46 CFR 112 requirements for emergency lighting and power systems include:

> "The prime mover of an emergency generator must be either a diesel engine or a gas turbine."

> "The emergency generator prime mover is to be rated for continuous service."

> "When the potential of the final emergency power source reaches 85 to 95 percent of normal value, the emergency loads under § 112.15-5 must transfer automatically to the final emergency power source and, on a passenger vessel, this transfer must be accomplished in no more than 45 seconds after failure of the normal source of power."

If energy storage is used as a Temporary Emergency Power Source, then …

> "Each temporary source of emergency power required by Table 112.05-5(a) must consist of a storage battery of sufficient capacity to supply the temporary emergency loads for not less than one-half hour."

Requirements for the emergency diesel / gas turbine generator set include:

"(d) The generator set must be capable of carrying its full rated load within 45 seconds after cranking is started with the intake air, room ambient temperature, and starting equipment at 0°C. The generator's prime mover must not have a starting aid to meet this requirement, except that a thermostatically-controlled electric water-jacket heater connected to the final emergency bus is permitted.

(e) The generator set must start by hydraulic, compressed air, or electrical means.

(f) The generator set must maintain proper lubrication when inclined to the angles specified in § 112.05-5(c), and must be arranged so that it does not spill oil under a vessel roll of 30 degrees to each side of the vertical.

…

(k) Each emergency generator that is arranged to be automatically started must be equipped with a starting device with an energy-storage capability of at least six consecutive starts. A second, separate source of starting energy may provide three of the required six starts. If a second source is provided, the system need only provide three consecutive starts."

The ABS MVR states:

"The electrical power available from the emergency source is to be sufficient to supply all those services that are essential for safety in an emergency, due regard being paid to such services as may have to be operated simultaneously. Where the sum of the loads on the emergency generator switchboard exceeds the power available, an analysis demonstrating that the power required to operate the services simultaneously is to be produced. The analysis is to be submitted for review in support of the sizing of the emergency generator."

For vessels 500 GT and over, "Unless instructed otherwise by the Flag Administration, the emergency generator may be used during lay time in port for supplying power to the vessel, provided …." additional requirements are complied with.

IEEE Std. 45.1 states:

"Emergency generator(s) should be sized to supply 100% of connected loads that are essential for safety in an emergency condition. Where redundant equipment is installed so that not all loads operate simultaneously, these redundant loads need not be considered in the calculation."

“Emergency generators should be capable of carrying a full rated load within 45 s after loss of the normal power source with the intake air, room ambient temperature, and starting equipment at a minimum temperature specified for the application.”

“Upon interruption of normal power, the prime mover driving the emergency power source should start automatically. When the voltage of the emergency source reaches 85% to 95% of nominal value, the emergency loads should transfer automatically to the emergency power source. The transfer to emergency power should be accomplished within 45 s after failure of the normal power source. If the system is arranged for automatic retransfer, the return to normal supply should be accomplished when the available voltage is 85% to 95% of the nominal value and the expiration of an appropriate time delay. The emergency generator should continue to run without load until shut down either manually or automatically by use of a timing device.”

“Regulatory requirements typically do not allow non-emergency loads to be connected to an emergency switchboard. However, for some complex designs such as naval combatants where an “emergency” generator provides back-up power for a limited amount of ship’s loads, then:

— For ready availability of the emergency source of electrical power to emergency loads, arrangements should be made, where necessary, to automatically disconnect non-emergency loads from the emergency power source upon loss of ship’s normal power.

— If any non-emergency loads are connected to the emergency switchboard and if the system is arranged for feedback operation (through the interconnection feeder), they should automatically be disconnected at the emergency power source upon detection of 95% of full load current of the emergency generator to prevent an overload condition.

— Protective devices and circuitry should be provided to automatically disconnect the interconnection feeder and any non-emergency loads should a main power failure occur while the emergency generator is running (i.e., exercising or testing).”

“The emergency switchboard should be arranged to prevent parallel operation of an emergency power source with any other source of electrical power (i.e., main power), except where suitable means are taken for safeguarding independent emergency operation under all circumstances. This will allow for the emergency generator to be used to supply non-emergency loads. This is useful when exercising and testing the emergency generator(s).”

4. References

IEEE Std 45.1, IEEE Recommended Practice for Electrical Installations on Shipboard—Design

46 CFR 111.10 Coast Guard, Department of Homeland Security, Electrical Engineering, Electrical Systems – General Requirements.

46 CFR 112 Coast Guard, Department of Homeland Security, Electrical Engineering, Emergency Lighting and Power Systems.

ABS Marine Vessel Rules

Dalton, Thomas, "Power Application Limitations of AC Shipboard Electric Plants for US Navy Ships," presented at ASNE TSS 2019, June 18-20, 2019, Washington DC.