Developing a generator set scheduling table

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1. Introduction

An important element of an Electrical Power System Concept of Operation (EPS-CONOPS) is a generator set scheduling table. This table indicates for a given range of electrical load, the online status of generator sets, and for those generator sets that are online, the method to determine how much power is provided by each generator set. Each operational condition may have a separate generator set scheduling table. Table 1 is an example of a scheduling table for a shipboard power system without energy storage and where the online generator sets are always paralleled. For this table the term "share" indicates that the ratio of the power provided by each online generator set to its rated power is the same for all online generator sets designated as "share." It is also possible for one or more online generator sets to have the amount of power provided to be a constant value; in this case either one generator set should be designated as a "swing" generator set to provide the difference between the online load and the sum of the constant powers provided by online generators, or more than one generator sets should be designated as "share."

The generator set scheduling table is used to determine the operating point (voltage, current, and power) of all generator sets when performing load flow analysis, voltage drop analysis, endurance fuel and annual fuel calculations. For the endurance fuel and annual fuel calculations, this operating point is then used to calculate the fuel rate for each online generator set; the sum of these fuel rates is the total fuel rate for the ship. For the other analysis, the operating points are used to determine current through distribution equipment and voltages at switchboards, load centers, and loads for the various operating conditions, ambient temperatures, switch positions, and bus transfer positions.

Table 1: Generator set scheduling table for system without energy storage example (Doerry and Parsons 2023)

		Generator set 1A	Generator set 1B	Generator set 2A	Generator set 2B
	Rating (MW)	20	5	20	5
Total load	up to 9.5	Offline	Share	Offline	Share
	9.5–23.75	Share	Offline	Offline	Share
	23.75–28.5	Share	Share	Offline	Share
	28.5–38	Share	Offline	Share	Offline
	38–42.75	Share	Share	Share	Offline
	42.75–50	Share	Share	Share	Share

For a given total load, the generator set scheduling table is usually designed to minimize fuel consumption while supplying the load and meeting operating constraints for power system reliability (Quality of Service (QOS)); and ensuring the generator sets are not overloaded due to load variation or inexact load sharing among paralleled generator sets.

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2. Operating constraints

Most commercial ships, and perhaps during some operational conditions for naval combatants, the electrical power system is operated as a single power system; all online generator sets are paralleled. For these operational conditions, the total online generation capacity multiplied by 0.95 should be no less than the electrical load. The factor of 0.95 is to account for load variation and imperfect sharing of power among paralleled generator sets. Furthermore, for power system reliability / QOS, the guidance from IEEE 45.1 should be followed:

From IEEE 45.1-2023 Clause 7.1.1

> "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."

See IEEE 45.1-2023 Clause 5.9 for guidance on QOS. The goal is to allow continued operation following loss of an online generator set, of all uninterruptible and short-term interruptible loads while shedding long term interruptible loads; the long-term interruptible loads can tolerate an outage while a standby or emergency generator set comes on line.

This guidance implies that if there is no or insufficient energy storage on the bus, that at least two generator sets are online at all time. Even with sufficient energy storage, the customer may require at least two generator sets be online at all time.

In some operational conditions, such as battle for naval combatants, and restricted maneuvering, the electrical power system is operated in "split plant." The power system operates as two independent systems. For these operational conditions, the total online generation capacity for each independent system multiplied by 0.95 should be no less than the electrical load for that system. For most ships, the IEEE 45.1-2023 Clause 7.1.1 condition is usually met in spirit through the use of automatic (ABT) and manual (MBT) bus transfers. Upon loss of power on one system, all vital loads (typically uninterruptible and short-term interruptible loads) are switched to the remaining, powered, system. This remaining energized system should have the capability to shed long-term interruptible load (if needed) to power (with all remaining online generator sets loaded at no more than 95% of rated power) all of its uninterruptible and short-term interruptible loads as well as the loads added from the de-energized system via ABTs and MBTs.

When operating in split plant, having only one online generator set for each independent system is allowable if that online generator set has the capacity to serve its own uninterruptible and short-term interruptible loads as well as those which may be added through ABT and MBTs.

The use of energy storage to power uninterruptible and short-term interruptible loads until an emergency or backup generator is brought online may be cost effective. If upon loss of a generator set the remaining generator set(s) do not have sufficient capacity to serve the uninterruptible and short-term interruptible loads, then energy storage with sufficient power and energy capability may be employed to serve these loads.

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Note that loads with dedicated un-interruptible power supplies with sufficient energy capacity to operate without power from the power system for at least several times longer than the generator start time should be considered long-term interruptible loads.

For integrated power systems, when the propulsion load is greater than 5% of the total rated power of online generator sets and the control system can control the propulsion power to prevent generator set overloads, then the online generator sets should be allowed to operate at 100% of rated capacity; otherwise, the online generator sets should operate at a maximum of 95% of rated capacity.

For QOS considerations, the propulsion load required to achieve a minimum speed is considered a short-term interruptible load; the remaining propulsion load is usually considered a long-term interruptible load and may be shed when there is insufficient power generation capacity.

When operating in split plant, it may be possible and beneficial to reallocate some loads from one of the independent systems to the other; doing so can minimize the total number of generator sets online as well as minimize the fuel rate.

In early concept exploration, the breakdown of loads into the QOS categories (uninterruptible, short-term interruptible, long-term interruptible, and exempt) is rarely known with precision. Usually, assumptions are made that should then be confirmed during preliminary design. These assumptions should be documented in study-guides and analysis reports. One should consider reserving space, weight, and services for energy storage should its need become apparent in preliminary design.

Generator sets have a desired minimum power level; operating below this power level is possible, but will likely result in increased maintenance. Diesel generator sets should normally operate at more than 50% of rated power; operating below 30% of rated power can result in significantly increased maintenance. Gas turbine generator sets should normally operate at more than 50% of rated power; the manufacture should be consulted to determine the impact of continuous operation below 50% of rated power.

For n generator sets, there are 2^n possible configurations of generator sets being online or offline. Each configuration should be evaluated against the constraints listed above to determine the minimum and maximum total load the configuration can support for each independent system. Using the example from Table 1 which employs four generator sets and no energy storage, 16 configurations are possible. Of these 16, five can be eliminated (in red) because they include fewer than 2 online generator sets. The minimum load in this example is set at 30% of the total rated power of the online generator sets. The maximum load is set at 95% of the total rated power of the online generator sets. The range of supported loads between the minimum and maximum loads for the remaining 11 configurations is displayed in Table 3. For total loads less than 3 MW, all configurations would be lightly loaded; configuration 5 would be the least lightly loaded and should be chosen to operate in this region. Only configuration 15 can support a total load greater than 47.5 MW; doing so would require advanced power system controls to prevent generator set overloads. Note that the ability to support uninterruptible and short-term interruptible loads with the loss of one generator set is assumed to be met with no further analysis.

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Table 2: Properties of Generator Set configurations

	Generator Set 1A	Generator Set 1B	Generator Set 2A	Generator Set 2B	Minimum load	At least 2 online	Maximum Load
Rating (MW) / Configuration	20	5	20	5	(MW)		(MW)
0	off	off	off	off	0	FALSE	0
1	off	off	off	on	1.5	FALSE	4.75
2	off	off	on	off	6	FALSE	19
3	off	off	on	on	7.5	TRUE	23.75
4	off	on	off	off	1.5	FALSE	4.75
5	off	on	off	on	3	TRUE	9.5
6	off	on	on	off	7.5	TRUE	23.75
7	off	on	on	on	9	TRUE	28.5
8	on	off	off	off	6	FALSE	19
9	on	off	off	on	7.5	TRUE	23.75
10	on	off	on	off	12	TRUE	38
11	on	off	on	on	13.5	TRUE	42.75
12	on	on	off	off	7.5	TRUE	23.75
13	on	on	off	on	9	TRUE	28.5
14	on	on	on	off	13.5	TRUE	42.75
15	on	on	on	on	15	TRUE	47.5

Table 3: Range of loads supported by each configuration

3. Energy Efficiency

Over most of the total range of loads depicted in Table 3, more than one set of configurations can meet the load while staying within constraints. Typically, one chooses to use the most economical configuration with respect to fuel consumption. Doerry (2022) provides a method for determining the most economical configuration based on assuming the fuel rate vs power curve can be approximated as a cubic polynomial. For early-stage design, a linear approximation should be sufficient and greatly simplifies the process of identifying the optimal configuration. If the fuel rate is not close to linear, the more detailed process in Doerry (2022) should be used.

Datasheets typically provide specific fuel consumption for a handful of power ratings. The fuel rate is obtained by multiplying the sfc by the corresponding power. Table 4 provides example sfc value and the calculated fuel rates for the example generator sets. These fuel rates can be plotted vs the power (MW) and the linear trendlines calculated as shown in Figure 1 and Figure 2.

The constant term for the linear trendlines can be viewed as the cost (in terms of fuel rate) of turning on the generator set and is independent of how much power the generator set provides. The linear coefficient is the incremental cost of providing power. For a given load power, the optimal operating point for a configuration with two different types of generator sets can be obtained by:

1. Set the generator sets with the higher linear coefficient to their minimum operating load. Set the generator sets with the lower linear coefficient to their maximum operating load. Sum the operating loads of all the online generator sets, call this value the transition power.

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2. If the given load power is not more than the transition power, leave the generator sets with the higher linear coefficient at their minimum operating load and divide the remaining given load power equally among the generator sets with the lowest linear coefficient.
3. If the given load power is more than the transition power, leave the generator sets with lower linear coefficient at their maximum operating load and divide the remaining given load power equally among the generator sets with the higher linear coefficient.
4. Calculate the fuel rates for all the generator sets individually, then sum them for a total fuel rate for the configuration.

If a configuration only has one type of generator set, the load power should be equally split among the generator sets. In general, assuming a linear fuel rate curve, the power provided by generator sets of the same type should be equal; variations in load are equally shared among the generator sets which minimizes control action (and fuel consumption) on the prime mover governors.

If there are more than two types of generator sets online in a configuration, then there may be more than one transition power. The general idea is that generator sets should be loaded in the order of their linear coefficient up to their maximum operating load, but no generator set should be below their minimum operating load.

For the example depicted in Table 4, the 20 MW generator set has the lower linear coefficient (even though it has a higher sfc). The transition power is equal to the minimum operating load (1.5 MW) of the 5 MW generator set plus the maximum operating load (19 MW) of the 20 MW generator set: 20.5 MW. Below 20.5 MW, the 5 MW generator set should be operated at its minimum operating load and the remainder of the load power should be provided by the 20 MW generator set. Above 20.5 MW, the 20 MW generator should operate at its maximum operating load and the remainder of the load power should be provided by the 5 MW generator set.

Table 4: sfc data and conversion to fuel rates for example generator sets.

20 MW Generator Set			
Fraction of Rated Power	Power (MW)	SFC (g/KW-h)	Fuel rate (kg/h)
0.50	10	328	3280
0.75	15	283	4245
1.00	20	261	5220
5 MW Generator Set			
Fraction of Rated Power	Power (MW)	SFC (g/KW-h)	Fuel rate (kg/h)
0.50	2.5	208	520
0.75	3.75	204	765
1.00	5	202	1010

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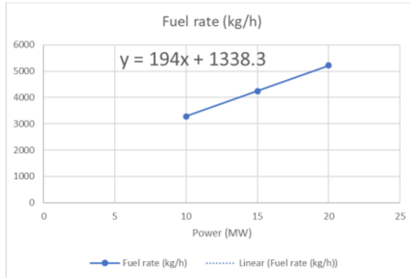

Figure 1: Fuel rate curve for 20 MW generator set

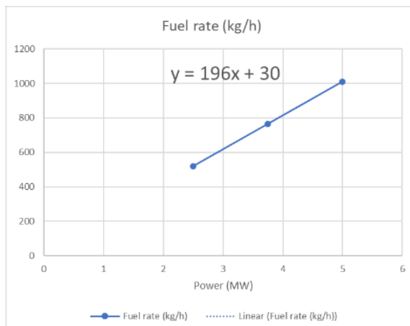

Figure 2: Fuel rate curve for 20 MW generator set

The next step in the process is to add rows in Table 3 for each of the transition powers, then calculate the fuel rate for each applicable row for each configuration. The results for the example are presented in Table 5. For any total load interval, the lowest fuel rate is in green; others are in red. For the first and last interval, generator sets are operating at either below their minimum operating load or above their maximum operating load. These results are used to generate the generator set scheduling table depicted in Table 6.

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Table 5: Fuel rates (kg/h) for configurations

Total Load	Configurations					
	3,6,9,12	5	7,13	10	11,14	15
0		60				
3		648				
7.5	2826	1530				
9	3117	1824	3150			
9.5	3214	1922	3247			
12	3699		3732	5005		
13.5	3990		4023	5296	5329	
15	4281		4314	5587	5620	5653
20.5	***5348***		5381	6654	6687	6720
22	5642		***5672***	6945	6978	7011
23.75	5985		6015	7284	7317	7350
28.5			6946	8206	8239	8272
38				10049	10082	10115
39.5					***10373***	10406
41					10667	***10697***
42.75					11010	11040
47.5						11971
50						12457
20 MW	1	0	1	2	2	2
5 MW	1	2	2	0	1	2
Transition Power (MW)	20.5	NA	22	NA	39.5	41

Table 6: Generator set scheduling table with optimal generator loading

Total Load (MW)	Generator set 1A (20 MW)	Generator set 1B (5 MW)	Generator set 2A (20 MW)	Generator set 2B (5 MW)	All configs
up to 9.5	offline	share	offline	share	5
9.5 to 20.5	swing	offline	offline	minimum	3,6,9,12
20 to 23.75	maximum	offline	offline	swing	3,6,9,12
23.75 to 28.5	maximum	share	offline	share	7,13
28.5 to 38	share	offline	share	offline	10
38 to 39.5	share	minimum	share	offline	11,14
39.5 to 42.75	maximum	swing	maximum	offline	11,14
42.75 to 47.5	maximum	share	maximum	share	15
47.5 to 50	share	share	share	share	15

In this example, the linear coefficients of the two types of generator sets do not differ significantly. This means that one can simplify the creation of the generator set scheduling table by assuming the online generators all share power in proportion to their rating. With this assumption, the fuel rates can be calculated as depicted in Table 7. The ratio of the fuel rates from Table 7 with respect to the fuel rates from Table 5 are shown in Table 8; the increase in fuel rates from simplification are very small. Using the simplifications, one can generate the simplified generator set scheduling table depicted in Table 9; this table is identical to Table 1.

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Table 7: Fuel rates (kg/h) for configurations assuming sharing of loads by rated power

Total Load	Configurations					
	3,6,9,12	5	7,13	10	11,14	15
0		60				
3		648				
7.5	2826	1530				
9	3118	1824	3150			
9.5	3215	1922	3248			
12	3701		3734	5005		
13.5	3993		4026	5296	5329	
15	4284		4318	5587	5620	5653
20.5	5354		5389	6654	6688	6722
22	5645		5681	6945	6980	7013
23.75	5985		6022	7284	7319	7354
28.5			6946	8206	8242	8277
38				10049	10087	10124
39.5					10378	10415
41					10670	10707
42.75					11010	11047
47.5						11971
50						12457
20 MW	1	0	1	2	2	2
5 MW	1	2	2	0	1	2
Transition Power (MW)	20.5	NA	22	NA	39.5	41

Table 8: Ratio of fuel rates from Table 7 with respect to fuel rates from Table 5

Total Load	Configurations					
	3,6,9,12	5	7,13	10	11,14	15
0		1				
3		1				
7.5	1	1				
9	1.00019	1	1			
9.5	1.00025	1	1.00010			
12	1.00049		1.00054	1		
13.5	1.00060		1.00075	1	1	
15	1.00070		1.00093	1	1.00006	1
20.5	1.00097		1.00142	1	1.00023	1.00033
22	1.00050		1.00153	1	1.00027	1.00040
23.75	1		1.00105	1	1.00031	1.00048
28.5			1	1	1.00040	1.00065
38				1	1.00054	1.00091
39.5					1.00056	1.00094
41					1.00029	1.00097
42.75					1	1.00069
47.5						1
50						1

Table 9: Generator set scheduling table with simplified generator loading

Total Load (MW)	Generator set 1A (20 MW)	Generator set 1B (5 MW)	Generator set 2A (20 MW)	Generator set 2B (5 MW)	All configs
up to 9.5	offline	share	offline	share	5
9.5 to 23.75	share	offline	offline	share	3,6,9,12
23.75 to 28.5	share	share	offline	share	7,13
28.5 to 38	share	offline	share	offline	10
38 to 42.75	share	share	share	offline	11,14
42.75 to 50	share	share	share	share	15

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4. References

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