Developing a generator set scheduling table

Shipboard Power System Fundamentals

Revision of 4 February 2026

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http://doerry.org/norbert/MarineElectricalPowerSystems/index.htm

Essential Questions

What is a generator set scheduling table and how is it used?	Understand
How is a generator set scheduling table developed for operating with all generators paralleled?	Apply
How is a generator set scheduling table developed for operating in split plant?	Apply
How is a generator set scheduling table dependent on an operating condition ?	Understand

Generator Set Scheduling Table

- For a given range of electrical load, provides recommendation for …
  - Online status of generator sets.
  - The method for determining how much power each online generator set provides.
    - Share – equally shares with other generator sets marked as share.
    - Constant power – provides a constant power (typically either Maximum or Minimum).
    - Swing – provides the difference between the total load and the power provided by all other paralleled generator sets.
- Usual Objectives …
  - Minimize fuel consumption.
  - Meet operating constraints for power system reliability (Quality of Service)
- Each operational condition may have its own generator set scheduling table.
  - Different operating constraints.
- In design, the generator set scheduling table ensures consistent generator set line-ups are used in simulation and analysis.
- The Generator Set Scheduling Table is usually incorporated into the Electrical Power System Concept of Operation (EPS-CONOPS).
- In operation, while the ship operators are not required to follow the generator set scheduling table, they should have a good reason to depart from it.

Example

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

Operating constraints

- Most commercial ships and some operational conditions for naval ships
  - Electrical power system normally operated as a single power system with all generator sets paralleled.
  - If sufficient energy storage not available, the total online generation capacity multiplied by 0.95 should be no less than the electrical load. (To account for load variation and imperfect power sharing)
  - For QOS considerations, IEEE 45.1 states …

> "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."

Operating Constraints (continued)

- Some operating conditions (such as battle for naval ships and restricted maneuvering) the electrical power system is operated in "split plant"
  - Power system operated as two independent systems.
  - Upon loss of power to one system, bus transfer devices switch mission critical loads to the powered system.
    - Powered system should have sufficient capacity after load shedding to serve the transferred mission critical loads.
  - May be possible to reallocate some loads from one independent system to the other to minimize number of online generator sets.
- Energy storage may prove useful
  - Provide capacity to satisfy QOS criteria
  - Enable generator sets to operate at full rating instead of 0.95 times full rating.
  - Enable operating with a single generator set online.
- Generator set minimum rating
  - Operating a generator set at low power levels possible, but may result in greater maintenance requirements; operating below the minimum rating should be minimized.
  - Diesel generator sets should normally be loaded to greater than 30% of rated power.
  - Gas turbine generator sets should normally be loaded to greater 50% of rated power.

Determining minimum and maximum load for different generator set line-ups.

- For n generator sets, there are 2^n possible configurations of generator sets being online or offline.
- For each configuration, calculate the minimum and maximum load.
  - Add up the minimum loads for online generator sets.
  - Add up the maximum loads for online generator sets.
- Eliminate configurations that don't meet QOS requirements.
  - If no energy storage, eliminate configurations with only one generator set.
- Group configurations that have the same minimum and maximum load.

	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

Configurations in red eliminated

Groups:
3, 6, 9, 12
5
7,13
10
11,14
15

Create range of loads graph

- Create a table where each row corresponds to a minimum or a maximum load a group of configurations can support.
  - Also include 0 total load and 100% of the rating of all generator sets.
- The columns correspond to the group of configurations.
- Color the cells green if the total load for the row falls between the minimum and maximum (inclusive) load for the group of configurations.
- For the first row, color the cell corresponding to the group of configurations that would be least lightly loaded yellow.
- For the last row, color the cell corresponding to the group with all generator sets online yellow.
- For remaining analysis, choose one configuration from each group of configurations as representative for the group.

Total Load	Configurations				
	3,6,9,12	5	7,13	10	11,14	15
0						
3						
7.5						
9						
9.5						
12						
13.5						
15						
23.75						
28.5						
38						
42.75						
47.5						
50						

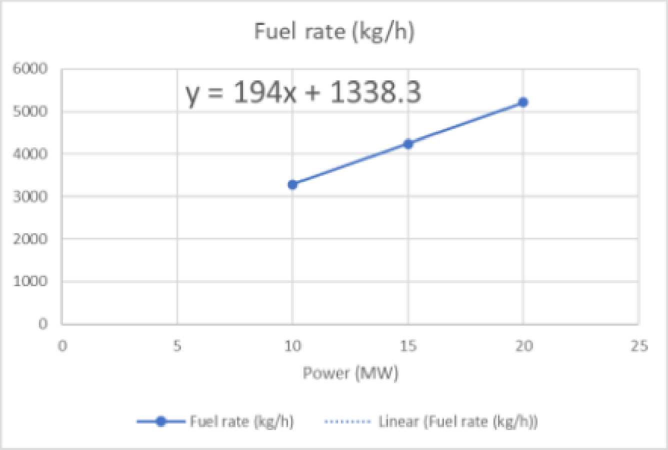
For a given total load, this graph indicates which group of configurations are feasible; still need to know which group of configurations is best.

Calculate Fuel Rates

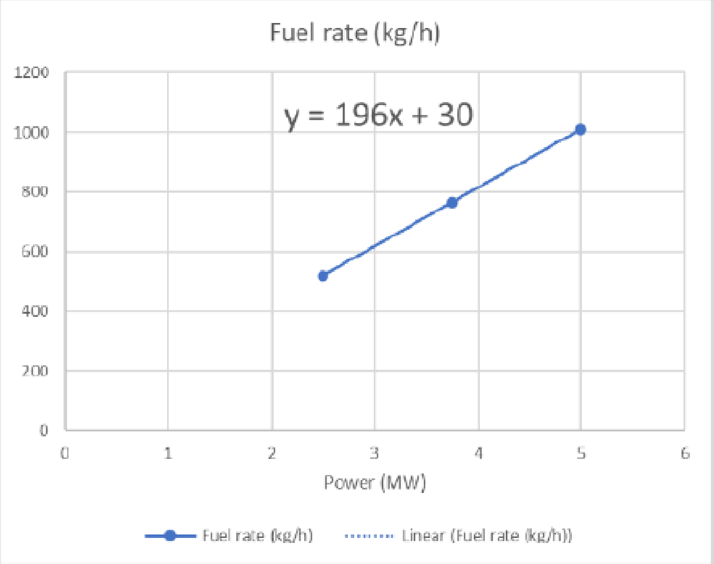
- Fuel consumption for generator sets typically provided as specific fuel consumption (sfc) for a few operating point.
- Best practice is to convert the sfc values to fuel rates, curve fit the fuel rate points, then use the resulting curve to estimate fuel rates for a given power level.

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



20 MW Generator set



5 MW Generator set

Optimal operating point for configurations with two different types of generator sets

- Assumes fuel rates are linear. More complex analysis is required if nonlinear or more than two types of generator sets.
- Set the generator sets with the higher fuel rate linear coefficient to their minimum operating load. Set the generator sets with the lower fuel rate linear coefficient to their maximum operating load. Sum the operating loads and call the sum the transition power.
- If the desired 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 desired load power among the generator sets with the lower linear coefficient.
- If the desired load power is more than the transition power, leave the generator sets with the 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.
- Calculate the fuel rates for all the generator sets individually, then sum for a total fuel rate for the configuration.

Modify the range of loads graph to include transition powers and add fuel rates

- Add rows for each configuration transition power.
- For each group of configurations, calculate the fuel rate for each row.
- For each row, color the cells with the lowest fuel rate green, all others color red.
- If in a column, the last colored cell is green, also color the cell for that row in the column with the second lowest fuel rate.
- For a given set of configurations, mark the fuel rate corresponding to the transition power (Bold italic in this case)

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

Create Scheduling Table

- Each column of green cells corresponds to one or two rows of the scheduling table.
  - If the green cells include the transition power, then create two rows
  - If the green cells do not include the transition power, then create only one row.

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Simplification

- In this case, the linear coefficients for the fuel rates of the two types of generator sets are nearly identical.
- Sharing power equally (as a fraction of rated power) results in less than 0.1% increase in fuel rate – well within estimation tolerances.
- Justifies simplifying the generator set scheduling table.

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