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A Probabilistic Method of Electric Load Analysis for Ships

by

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Engineering analysis often involves simplifications to keep the labor of calculations within tractable limits and the time involved to carry these out within reasonable bounds. In some instances, it is possible to set a desired level of accuracy and have a choice about the most appropriate approach. In other instances, an engineer has to contend with the fact that the degree of accuracy is already limited by the methods at hand.

Easy access to computers has forced engineers to rethink traditional solutions to problems of analysis and design. The idea of what is tractable, the limits of accuracy and the definition of an economic approach have to be seen in a new light.

The field of ship design, like other engineering fields, is replete with stock solutions to stock problems. Stock problems will remain, but innovative computer-aided solutions must be sought. The fact that the traditional approaches have passed the test of time is no excuse for stagnation.

This paper describes a new solution to the problem of electric load analysis for ships for purposes of generator sizing. The traditional method, which is executed and presented in a standard format, is one which naval architects and marine engineers immediately recognize, understand and respect. It can, without much disagreement, be said to be the best that can be done within the limitations of the amount of calculations that have to be done without the benefit of a computer.

The proposed computer-aided method, significantly released from the constraints of computing time, tries to improve upon the traditional method by reducing the degree of simplification in the underlying assumptions and by giving more information about the nature of anticipated electrical load. This is done without necessarily prolonging the time directly spent by the designer on the problem, exclusive of computer execution time.

Introduction

The traditional procedure of sizing electrical plants aboard ships involves the following steps:

1. A determination of the probable peak loads at sea, during maneuvering and in port by means of an electric load analysis;

2. The determination of alternatives (number and individual rating of generators) based on the peak loads; and
3. The selection of the best alternative based on first cost, size and weight and degree of product standardization.

The analysis part gives a detailed tabulation of the connected load and operating load of each piece of electrical-driven device or other loads. To determine the operating load, a service factor is applied to the connected load of each item for each mode of ship operation (at sea, maneuvering, in port). This service factor represents a combined load factor and diversity factor expressing the percent of an equipment's own possible maximum which is contributed to the load on the generator plant over 24 hours. A single summation of the operating loads over all items for each mode is carried out to get the probable peaks, which are then used in the subsequent steps of generator sizing.

The selections of the service factors, which embody the probabilistic nature of the loads, involves a judgment call tempered by experience. The success of the method can perhaps be attributed to the long experience stamped on each of these factors.

This paper presents, mainly by way of examples, a method of analysis that outputs not just peak loads but also electrical demand profiles for each ship operating mode, as well as for overall ship operation. These profiles show the number of operating hours per year at different kilowatt demand levels. In addition to the probable peaks, the profiles also indicate the dominant range(s) of KW demand and the load characteristics at the high and low extremes.

With such an output, the latter steps of the selection process become more informed. The alternatives are chosen based not only on the peaks but also on the dominant range and the low extremes. The high extremes become useful not only in identifying the peaks but also in determining the amount of load management that may be required when operating in this range. Thus, to the third step in the process – the final selection – another criterion is added, the ease or difficulty of load management.

With such an output, the fuel cost estimate becomes more reliable since the duration at different load factors of the prime mover can be projected.

The Proposed Method

Inputs, Process, Outputs

The inputs to the procedure are:

1. duration of summer/winter ambients;*
2. duration of ship operating modes (fronthaul, backhaul, maneuvering and in port);
3. time working in port and time waiting in port; and
4. KW consumption and frequency of use of individual or groups of electrical loads.

*A license is employed in the definition of summer and winter. To wit, summer is when the air conditioning system must be turned on, and winter is otherwise.

See Table 1 for a sample input form. This is for a 36,000 DWT Open Hatch Ship with gantry crane.

The process which these inputs undergo is shown in Figure 1. The computer program considers all possible combinations of simultaneous loading from the different electrical load items and computes the total KW demand and duration (combined frequency) for each such combination. The different combinations are then grouped in brackets of KW demand at 100 KW increments and the total duration for each bracket is determined.

As outputs, annualized electrical demand profiles – overall and for each ship operating mode – can then be drawn showing the number of operating hours per year at different electrical demand levels. See Figure 2.

Randomness, Constraints

In the case referred to above, the only constraints imposed on all possible combinations of loads are those based on ambients and on operating mode, as shown in Figure 1. Otherwise, the profile generated may be said to be based on totally random combinations.

An equipment or group of equipment may have one of different numbers of conditions:

One (1) condition – always "on" and drawing rated power;

Two (2) conditions – "on" or "off" and drawing rated power when on;

Three (3) conditions – drawing 100 percent power, 80 percent power or 65 percent power (as in reefer containers at sea); or

Four (4) conditions – connected load, peak load, average of loads other than peak, "off" (as in gantry crane).

In Table 1, the duration of each condition of each item are given variously as percent of time, hours per voyage or percent of time while in use – depending upon what is intuitively easier to estimate. "Percent of time" assumes continuous use of the equipment for the relevant operating mode. "Percent of use" assumes that the equipment is used only for a fraction of time in the relevant operating mode.

In all cases, when reduced to fractions of time, the sum of durations of all conditions for any equipment over the relevant mode must be equal to unity.

With the previous note made about the randomness of the combinations, the number of all possible combinations can be simply determined (even by hand) using the laws of probabilities. Also, the sum of all the combined frequencies for the whole range of KW loading must be equal to unity if the duration of all conditions is expressed as time fractions. These two observations are used to check the correctness of the computer program.

Simplifying Assumptions

Groupings of Electrical Load Items

The case of the 36,000 DWT O/H Ship considered above involves 7,680 combinations and takes just under two hours to run in an HP-86 personal computer. Another case – that of a 190 FEU geared reefer containership (results of which are shown in Figure 3) – involves some 60,000 combinations and takes about 6 hours to run in the same computer.

It may be noted that, essentially, the number of combinations grows exponentially. If an item, which is not constrained by ship operating mode, is added, the number of combinations increases by a factor equal to the number of conditions associated with that equipment. If the item is constrained by operating mode, the effect is not as much.

To prevent nanoseconds from accumulating into days, reasonable simplifying assumptions have been introduced in the two cases above. Some items are assumed to be "on" or "off" simultaneously. These are considered as only one item of load. This assumption is easily acceptable in the case of propulsion auxiliaries, generator auxiliaries and steam auxiliaries. These three groups each account for a large number of small items. In the case of work equipment and hotel auxiliaries, the effect of the grouping is not critical since each of these is composed of a few small items.

The number of groupings can then be adjusted to obtain a reasonable amount of computer run time. If the company owns its computer, the desirable length of run time can depend upon how tight the schedule of the computer is. An overnight run appears to be logical since it leaves the computer free for other tasks requiring operator presence during the day. A weekend run is also a possibility.

Power Drawn by Equipment

Ideally, in-service data showing the behavior of each item in terms of actual power drawn and frequency for each level of consumption should be used. A model of the behavior of each equipment can be constructed to suit the proposed method.

Such information are largely unavailable at present. It may be sumised that this is so since the traditional method, employing as it does a single combined load and diversity factor, does not require such. Just as it took time to refine the service factors, so will the building up of these models of behavior take time.

In the two cases cited above, there is an attempt to create models for the gantry crane, reefer containers and mooring winch – all large-KW items. For all other items it is assumed that the power consumption is equal to the rated power (or sum of rated powers in the case of groupings). In the preliminary stage of design, what is determined is the minimum required power for an equipment. No nameplate values are employed. Thus the rated power is taken as the minimum required power.

For the gantry crane, manufacturers' literature and some bits of in-service data have made it possible to create a credible model. Peak load is taken as 83 percent of connected load and occurs 40 percent of the time when the crane is operating. Overall average consumption is taken as 60 percent of the connected load. From these, it is possible to get the average of all loads other than peak and get the duration for such load level. To account for inrush current, it is assumed that, for a very short period of time, the crane operates at a power equal to the connected load. Including the "off" condition, four states and their corresponding durations are defined for the gantry crane.

Generator Selection

Load Management and F.O. Consumption

As stated previously, the electrical demand profiles generated by the proposed method of analysis are random. The occurrence of the peaks are, however, subject to human control. The actual peak loads can be managed by deliberately delaying the operation of a certain item or items, either manually or by automatic means, while another item (or items) is running. Also, stopping operation of certain item(s) when it is desired to operate other item(s) – or "load shedding" – can be resorted to. Changing the random profile by the abovementioned means to keep the load factor on any running generator below a certain maximum allowable value is herein referred to as load management.

In selecting the generators, the random profiles are used as bases. The possible sizes are determined with consideration for the possibilities of load management. Thus the generator sizes need not necessarily cover the random peaks but has to be sufficient for the managed peak loads.

The demand profiles are particularly useful in determining the amount of time to be spent in and difficulties of managing the load. Since the durations of KW demands near the peaks are estimated by the proposed method of analysis, the number of hours to be devoted to load management per year for each alternative generator size can be calculated and compared. This is not possible within the traditional method.

The demand profiles also make possible a more reliable estimate of fuel oil (F. O.) consumption, the importance of which cannot be understated since F.O. expenses now dominate all other items under operating expenses. Whereas the traditional approach necessitates a very rough approximation of an average load factor to get F. O. consumption, the overall electrical demand profile in the proposed method becomes the basis for getting the duration at different load factors for each alternative generator size. In conjunction with the specific fuel consumption curve of the prime mover, it is then possible to get a close estimate of annual F.O. expenses. An accompanying short computer program using the output of the profile-generating program as one of its inputs has been written to estimate F.O. consumption.

Example 1:36,000 DWT O/H Ship

This example considers diesel engines as prime movers. It is common practice to limit the load factors on these engines to 90 percent and below. Redwood No. 1 1500 sec (R1500) fuel is used by the bigger engines when the load factor is above 50 percent. When the load factor falls below 50 percent, there is a shift to the lighter Marine Diesel Oil (MDO) to keep the engine working properly.

One operating year has been set at 350 days (8400 hours). July 1983 oil price levels in the U.S. West Coast are used – 300 $/tonne for MDO and 200 $/tonne for R1500.

Figure 1 shows that the overall predominant range of KW demands is from 400 to 700 KW. This is basically a reflection of the demand profile at sea. The peak load of 1700 KW occurs in port during summer with all electrical loads associated with this mode running. The lower extreme loads, 200 to 400 KW, also occur in port when the propulsion auxiliaries are dead.

There are certain trade-offs to be made in size selection. Bigger size generators can accommodate the peak loads with relatively little degree of load management but may be forced to run under 50 percent load factor (and thus use more expensive fuel) for greater lengths of time. Smaller generators, on the other hand, can handle the peak loads only with relatively greater degree of management but may generate savings in fuel because of more favorable load factors at the low extremes.

Three generator sizes are evaluated — from a small rating that requires some reasonable degree of load management to a rating that can accommodate the overall peak with practically no management.

Table 3 shows a comparison of annual F.O. expenses and time spent in load management for the sample diesel-generator sets.

A sample output from the program that computes overall F.O. expenses is shown in Table 2 for the 3 x 830 KW alternative.

The number of hours of load management can be picked up from outputs similar to that shown in Table 2 for the different modes of operation. It is required in this particular case that only one generator set be operated during maneuvering and at sea. Thus, when the load exceeds 90 percent on this single set, load management must be resorted to instead of throwing in a second set.

The 950 KW generators have a load factor below 50 percent in the 400-500 KW range, which accounts for 2,500 hours per year. This is the main cause of the much higher F.O. expense figure for this alternative. The 830 KW generators have a slightly lower F.O. cost than the 790 KW generators since they can still run on R1500 in the 700-800 KW range.

The most rational choice appears to be the 830 KW generators.

What remains is a further investigation of aspects of load management, delving deeper into the particulars of which equipment cannot run simultaneously under what operating mode for this choice. It turns out that the operation of the bilge, fire and general service, transfer and ballast pumps can be played with to attain allowable load factors at sea and during maneuvering.

Example 2: 190 FEU Geared Reefer Containership

Figure 3 shows an interesting profile for a reefer containership. Unlike the previous example, this profile has two dominant ranges of KW demand. The lower KW ranges are associated with the backhaul when the containers are empty.

For fuel economy the question arises of whether to use 4 big generators or a combination of 2 small and 2 big generators A big generator will experience difficulty in handling the 300 to 500 KW range.

The proposed method shows that the combination 2 x 500 KW + 2 x 1200 KW generators will indeed consume less fuel than a 4 x 880 KW alternative.

The final selection must, however, still take into account other considerations that come to the fore in this case. Is it possible to get standard bore engines with variable number of cylinders? If not, is it acceptable to keep two sets of spares? What size generator should be used as standby to go with the 500's and 1200's?

Further Studies

A. Shipboard measurements of electrical consumption can be conducted to check the projected demand profiles. Also the in-service behavior of electrical equipment can be studied.

B. The results of this proposed method of analysis can conceivably be made to dovetail with programmable control equipment aboard ships for purposes of load management.

C. The method was developed in the course of the actual design of ships that are now being built or are still being designed. Due to time constraints, the programs are tailor-made to fit specific ships. A versatile program that can handle all ship types is still to be developed. Account can perhaps be taken of electrical load variation within a 24-hour period, which may have some predictable elements – like the accommodation lights being on only at night or galley equipment being used only at certain times of day.

D. While this method has been developed for ships, it may be possible that some land-based installations may benefit from this type of an analysis.

Acknowledgements

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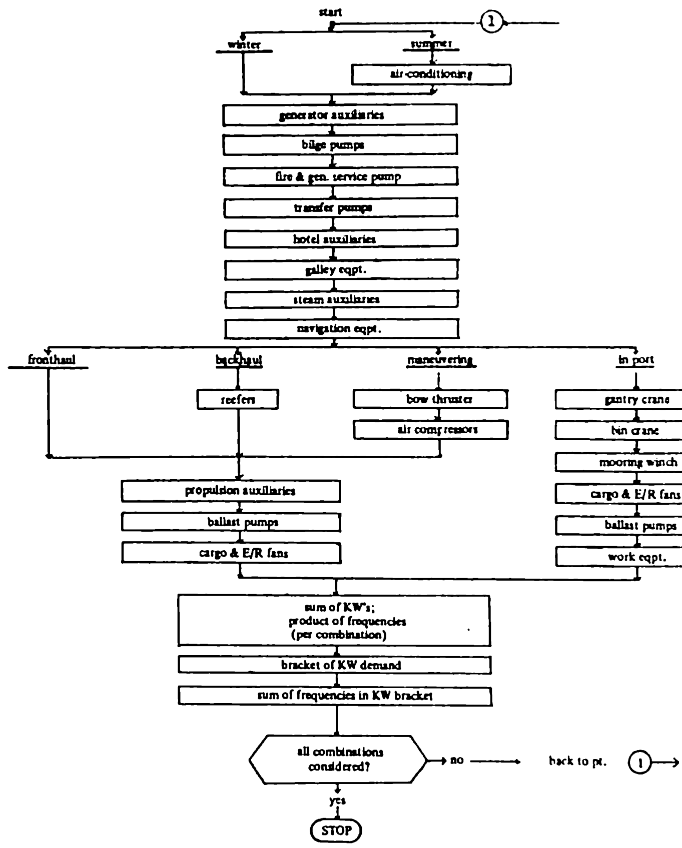

FLOW CHART

Figure 1.

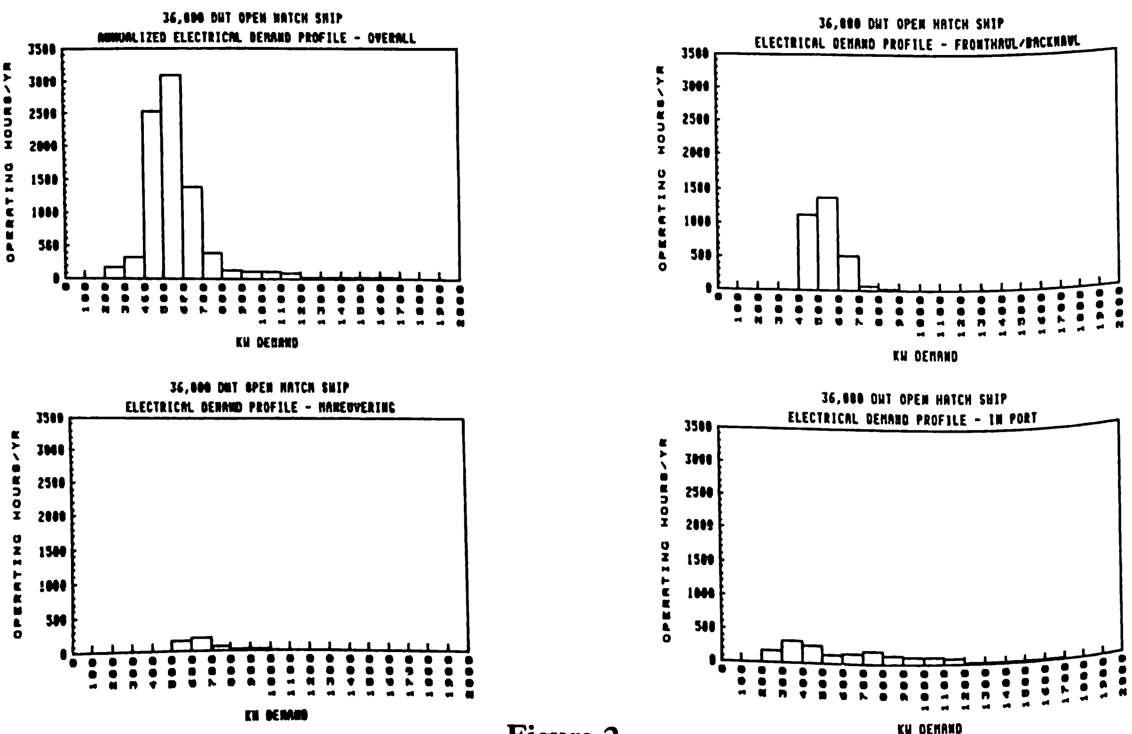

Figure 2.

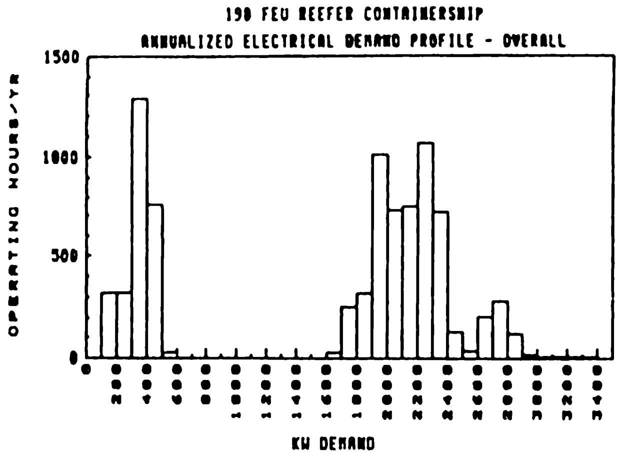

Figure 3.

Table 1

36,000 DWT OPEN HATCH SHIP
INPUT DATA
BASIC VOYAGE

ITEMS OF LOAD		DURATION
AMBIENTS:		MOS/YR
SUMMER		6
WINTER		6
OPERATING MODE		DAYS/VOYAGE
NORMAL SEA-GOING, FRONTHAUL		27.78
NORMAL SEA-GOING, BACKHAUL		27.78
MANEUVERING		4.00
IN PORT		15.48
	KW LOAD	% OF TIME
CONTAINER REFRIGERATION (IN PORT/MANEUVERING):		
COOLING DOWN, 100% LOAD FACTOR	0	25.0
COOLING DOWN, 80% LOAD FACTOR	0	75.0
CONTAINER REFRIGERATION (NORMAL SEA-GOING):		
COOLING DOWN, 100% LOAD FACTOR	0	10.0
COOLING DOWN, 80% LOAD FACTOR	0	20.0
KEEPING TEMP., 65% LOAD FACTOR	0	70.0
ENGINE ROOM EQUIPMENT:		'ON' WHEN:
PROPULSION AUXILIARIES	250	M/E RUNNING
DIESEL GENERATOR AUXILIARIES	16	D/G RUNNING
STEAM AUXILIARIES	24	BOILER 'ON'
		HRS/VOYAGE
BALLAST PUMP 'ON' (IN PORT)	100	100.0
BALLAST PUMP 'ON' (AT SEA/MANEUVERING)	100	140.0
BILGE PUMP 'ON'	12	180.0
FIRE & G.S. PUMP 'ON'	62	180.0
TRANSFER PUMPS 'ON'	20	180.0
WORK EQUIPMENT 'ON'	45	90.0
		% OF TIME
REEFER COOLING SYST 'ON' (IN PORT/MANEUV)	0	85.0
REEFER COOLING SYST 'ON' (AT SEA)	0	68.0
HOTEL AUXILIARIES 'ON'	77	70.0

MOORING WINCHES:		% OF USE
AT FULL POWER	220	10.0
AT HALF POWER	110	90.0
		% OF TIME MANEUVERING
BOWTHRUSTER	0	25.0
GANTRY CRANE:		% OF USE
PEAK LOAD	664	[illegible]
AVERAGE OF OTHER LOAD LEVELS	357	28.8
CONNECTED KW	800	.5
		HRS/VOYAGE
BIN CRANE	38	20.0
CARGO & E/R FANS:		% OF TIME
AT SEA/MANEUVERING	106	100.0
IN PORT	53	100.0
AIR COMPRESSORS:		HRS/VOYAGE
MANEUVERING	101	96.0
HOTEL LOADS		% OF TIME
AIR CONDITIONING (FANS/COMPRESSORS)	104	80.0
GALLEY & LAUNDRY EQUIPMENT	86	30.0
NAVIGATION EQUIPMENT	8	100.0

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Table 2
36,000 DWT OPEN HATCH SHIP
FUEL OIL CONSUMPTION
OVERALL
3 x 830 KW

KW	HRS/YR	D/G'S ON	%LOAD	FUEL	TONS/YR	US$/YR
0 TO 100	0.000	–	–	–	0.00	US$ 0.00
100 TO 200	0.000	–	–	–	0.00	0.00
200 TO 300	178.832	1	30	MDO	11.78	3533.85
300 TO 400	337.319	1	42	MDO	29.44	8832.02
400 TO 500	2522.839	1	54	R1500	283.85	56769.38
500 TO 600	3075.301	1	66	R1500	415.85	83169.78
600 TO 700	1390.584	1	78	R1500	220.88	44175.61
700 TO 800	398.627	1	90	R1500	73.19	14638.30
800 TO 900	141.414	2	51	R1500	30.27	6054.34
900 TO 1000	121.007	2	57	R1500	28.59	5718.03
1000 TO 1100	122.485	2	63	R1500	31.72	6343.35
1100 TO 1200	81.299	2	69	R1500	22.94	4588.29
1200 TO 1300	26.229	2	75	R1500	8.01	1602.99
1300 TO 1400	3.756	2	81	R1500	1.24	247.78
1400 TO 1500	.296	2	87	R1500	.11	21.02
1500 TO 1600	.012	2	93	R1500	.00	.90
1600 TO 1700	.000	2	99	R1500	.00	.01
1700 TO 1800	0.000	–	–	–	0.00	0.00
1800 TO 1900	0.000	–	–	–	0.00	0.00
1900 TO 2000	0.000	–	–	–	0.00	0.00
TOTAL	8400.000					US$ 235695.65

Table 3
COMPARISON OF ALTERNATIVES
36,000 DWT O/H SHIP

No. X KW RATING	F.O. EXPENSE ($/YR)	HOURS/YR OF LOAD MANAGEMENT				
		FRONTHAUL	BACKHAUL	MANEUVERING	IN PORT	TOTAL
3 X 790 KW	239,600	70	70	85	0.31	225
3 X 830 KW	235,700	35	35	43	0.01	113
3 X 950 KW	259,100	2	2	5	0.00	9