CABLE RATING
FOR THE
T45 HIGH VOLTAGE SYSTEM

BY

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ABSTRACT

The T45 propulsion power system comprises two switchboards, linked by an interconnector. Each switchboard is fed by a WR21 GTA and a ~ 2MW DG, and supplies a transformer for ship services and a propulsion motor through a static converter. The critical requirement addressed in this article is the installation of cables between the GTA and the switchboard, which is space limited. A minimum number of cables, with maximum flexibility is demanded.

By examining the rating of the circuit, its duty cycle and the available materials for making electric cable, an argument is made for intelligent design of the cable installation. It is concluded that cabling for the T45 power system can be designed to be over-run in the full load condition without prejudicing its through-life performance, with potential savings over 30% in material and installation cost, weight and space.

Introduction

The rating of electric power cables can be read from International Specifications or suppliers' brochures. Unquestioning application of this information can lead to a no-risk, costly and inefficient design, whereas a deeper understanding of the underlying technological opportunities can yield a better engineered solution.

This article explores some of the engineering calculation behind the rating of electric cable, and then demonstrates how application of this knowledge can be used to give a coherent design solution for a current warship project.

How Power Cables are rated

The capability of an electric cable to transmit power is limited by its operating voltage, and the current flowing in the circuit. The maximum operating voltage is defined by the quality of the insulation, and the system designer has little influence once the system voltage is selected. The maximum current, on the other hand, is determined by the allowable temperature rise of the conductor; this is influenced by several physical factors.

The main assumptions in published ratings for ship wiring cable are; an ambient of 45°C, single cable laid horizontally, in still air. The current rating is that which gives a specified conductor temperature under these conditions - currents used to be determined for 85°C conductor (40°C rise), but the same figures are now quoted for 90°C, to align with other international specifications. Table I shows the rating of various cross-sections of cable, together with their heat loss at full load, and a relationship to surface area.

TABLE 1 – *Cable cross-sections, current rating, heat dissipation.*

Cross-section mm^2	Rated current, amps	Power loss/metre W	Surface area/metre	W/unit surface area
95	290	20.2	58.7	0.34
150	385	23.0	70.4	0.32
185	440	24.2	77.0	0.31
240	520	25.7	85.8	0.30
300	590	26.1	93.9	0.28
400	670	27.0	105.5	0.26

A number of derating factors can be applied to the current rating to reflect the real world:

- Corrections for expected ambient temperature.
- Bunching factors to adjust for several cables in a loom.
- A paralleling factor for uneven current sharing in paralleled cables.

This calculation process is quite straightforward and would seem to constrain the system designer, until we consider the nature of cable insulation and sheathing materials.

Cable material characteristics

The materials used for electrical insulation and sheathing power cable are modified hydrocarbons (exceptionally are silicone compounds or mineral insulation), and broadly fall into two families; thermoplastics and elastomers (thermosets). It is unfortunate that the same current ratings may be quoted for the different materials, because their behaviour is definitely not the same.

Thermoplastics are attractive because they are cheap and easy to process, for example PVC or polythene. There is a definite upper temperature limit which is set by the softening point of the compound – beyond this temperature a conductor could migrate through the insulation and cause a short circuit or ground fault. Even below the softening point, thermoplastics can be susceptible to creep over the very long installed life that is the modern designer's aim, typically over 30 years.

On the other hand, thermoset materials require additional processing to promote cross-linking between the molecules of the compound. This cross-linking 'freezes' the structure of the product, and results in materials with rubber-like properties (elastomers) or with much increased melting points (XLPE, cross-linked polythene). The properties of an elastomer are preserved over a large temperature range, so there is no singular upper temperature limit, in contrast with a thermoplastic. Instead, thermal decomposition gives a boundary to the useful range of the material.

The degradation of a cross-linked material follows an exponential inverse relationship with absolute temperature. Alternatively, the life of the material, as measured by some critical characteristic, doubles for a decrease in temperature of typically 10°C. Mathematically, this relationship is defined by the Arrhenius equation,

$$K(T) = A\exp\frac{-E}{RT}$$

which transforms to:

$$\mathrm{In}\,K(T) = RT + \frac{-E}{C}$$

Where:

$K(T)$ is the reaction rate.	E is reaction energy.
R is the gas constant.	T is absolute temperature.

A and C are constants.

Cable materials are characterized by measuring the time taken for the elongation of break of a tensile test specimen to fall to 50%, when held at a constant temperature. A number of sets of specimens are kept at different temperatures, and the results plotted on a graph with axes of $\frac{1}{T}$°K, and Log (time).

(FIG.1) shows typical data for EPR, used for electrical insulation. The significance of the 50% elongation at break is that it equates to the strain imposed when a cable is bent around itself. This is much more severe than the recommended minimum radius of 6d.

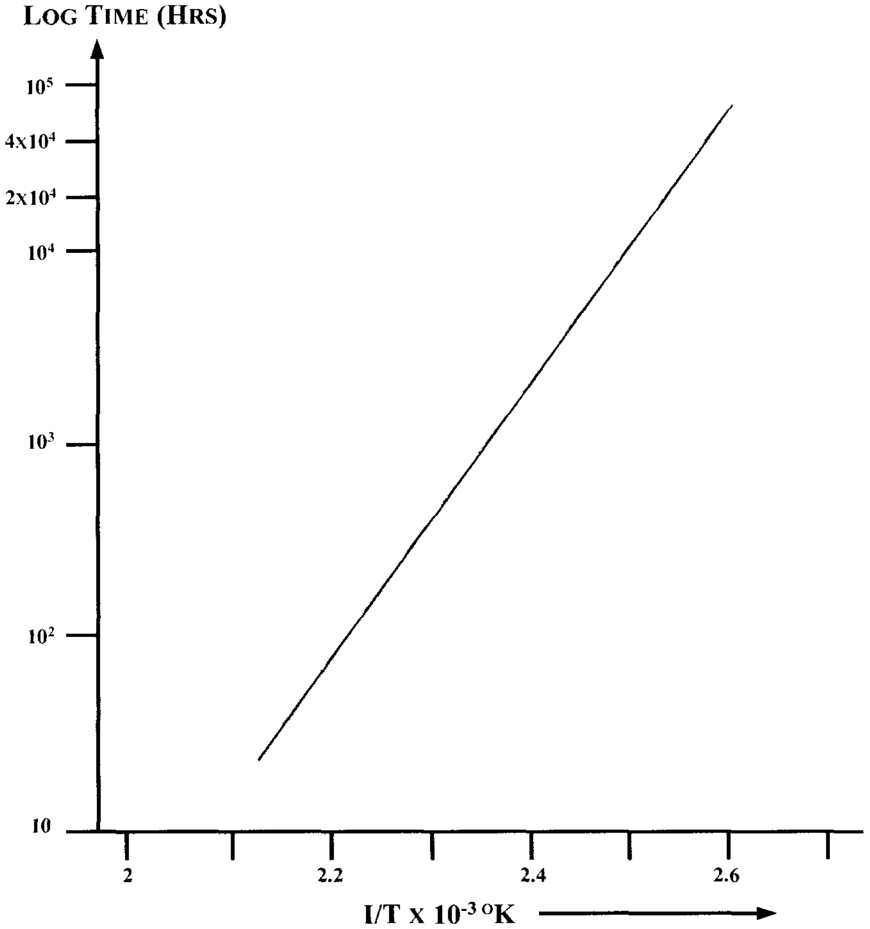

FIG.1 -- ARRHENIUS PLOT FOR AN EPR COMPOUND USED IN POWER CABLES (NOT TO SCALE)

Table2 shows the operating temperature versus life data for a range of materials used in cable manufacture. It is normal practice for naval shipbuilding to aim for at least 40,000 hours, at the rated conductor operating temperature; or very roughly 5 years continuous service. Given the duty cycle of the ship (sea, harbour, or upkeep) and the normal expectations for ambient temperature and load diversity, this target life (40,000 hours), is more than adequate to ensure a true life of over 30 years. Survey reports and service experience confirm this.

TABLE 2 – *Material life (hours) and temperature characteristics (°C)*

Hours	EPR	Silicone*	CSP	DStan61-12 Pt31
40,000	108	165	78.4	113
20,000	115	181	86	120
10,000	122	197	94	128

* at 30% EaB

Opportunities for Engineering

The rise of conductor temperature above ambient (ΔT) in an electric cable is to a first approximation directly proportioned to the heat released in it. The heat released is proportioned to the square of current (I) flowing. Hence,

$$\Delta T = BI^2$$

One option is to change the proportionality constant (B), by arranging for forced convection heat transfer from the cable – recall that its rating is based on natural convection in free air. Another option is to permit a higher current in a cable, at the expense of a higher temperature rise and, in an elastomeric cable, a shorter continuous service life. Table 3 gives an illustration of this for EPR. (EPR is the insulation of choice for HV and general power shipwiring cable). The corollary of accepting shorter continuous service is that the duty cycle of the system is well understood, so that the true life of the cable still matches or exceeds that of the platform.

TABLE 3 – *Correlation of life with current for EPR*

Life (hrs)	**263,000 ***	**80,000**	**40,000**	**20,000**	**10,000**
Current (per unit)	1	1.15	1.2	1.27	1.34

* Calculated from Arrhenius plot

Trading off the life of the cable with higher current capacity is not to be confused with the existing advice on short-term rating. Half-hour and one hour ratings are calculated on the basis that the total heat energy released into the cable is the same as that from continuous loading over the thermal time constant of the cable, typically 3 to 4 hours. In this way, the conductor temperature does not exceed the rating figure (e.g. 90°C). Typically a short-term rating could be used for a bow thruster, a deck crane, or a pulse-power system, where the duty is for a short period or intermittent. The life trade-off concept can be applied where the maximum load is continuous, several hours or days, but does not occur often. Examples are full power for electric propulsion, emergency interconnectors in a power system, maximum activity loads.

An example from a topical design serves to illustrate the potential savings that the life trade-off concept could achieve.

The Type 45 Power System

The Type 45 propulsion power system (FIG.2) comprises two switchboards, linked by an interconnector. Each switchboard is fed by a WR21 GTA and a ~ 2MWDG, and supplies a transformer for ship service power and a propulsion motor through a static converter. A harmonic filter is also attached to the switchboard.

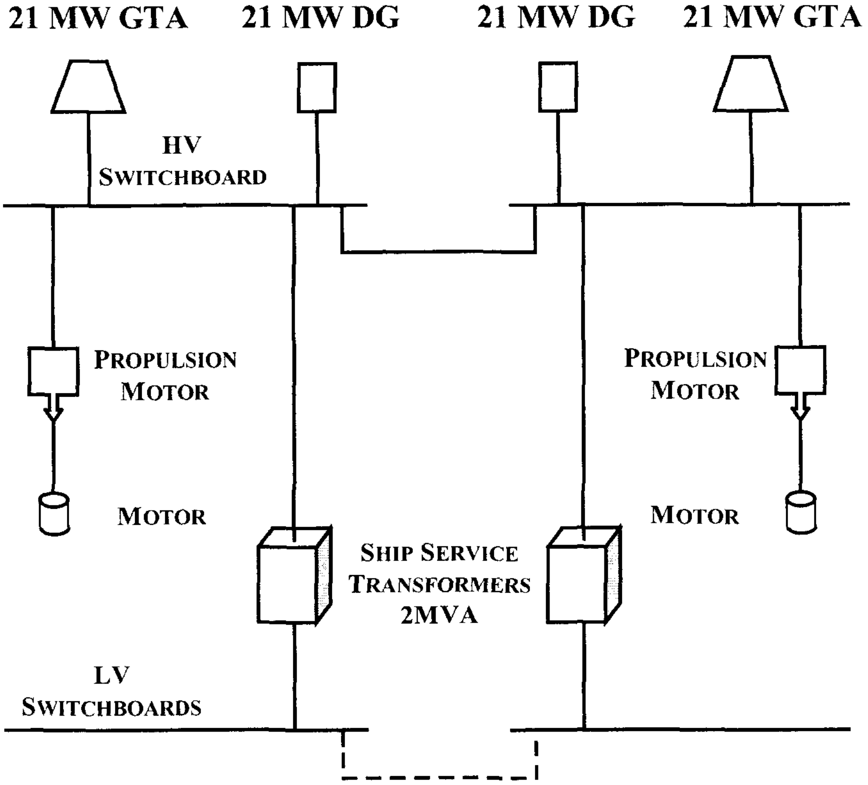

FIG.2 – TYPE 45 ELECTRICAL POWER SYSTEM

For the purpose of calculation:

- The system operates at 4160V, 3 phase 60Hz.
- The GTA rating is 21MW @ 0.9 power factor.

  The cables are run as single cores, arranged in trefoil; there is no neutral in the circuit. To obtain the current rating, a number of cores are paralleled to form the circuit.
- The ship spends 45% of its 30 year life at sea, of which 5% is in the full power band.
- The environment does not exceed 50°C in the vicinity of cables, shutdown conditions excepted.

From these figures, the GTA-switchboard circuit is required to carry 3,240 amps, using this as an example of the highest capacity circuit. The power factor of 0.9 is justified because most of the load is rectified in the propulsion converter and the harmonic filter attached to the busbars assists in power factor correction. There is no major induction motor load as on a LV system.

The total number of hours at full power over 30 year's platform life is 4,600, from the figures above.

Cable Sizes and Current Rating

Practicably, two sizes of conductor 300mm^2 or 400mm^2 could be used for this application, as the best compromise between numbers and ease of installation. Table 4 shows the number of conductors that could be needed if the solution is calculated on a conventional basis. Table 5 derives the life of cable if subject to an overload current by design.

TABLE 4 – *Number of cables for 3240A – conventional calculation*

Conductor	**Rating***	**Rating @ 50°C**	**No of parallel cables**	**Bunching**	**Paralleling**
300	590	555	5.8	471 (6.9)	424 (7.6)
400	670	630	5.14	535 (6)	481 (6.7)

(No of parallel cables, conventionally these figures are rounded up)

* iaw IEE Regulations for Electrical and Electronic Equipment of Ships

TABLE 5— *Number of cables for 3240A – Life Trade off calculation*

Conductor	**Rating**	**No of cables**	**Curent Factor**	**Heat Factor**	**AT**	**Conductor**	**Town Life**
300	590	5.49 (5)	1.1	1.2	54	104	80,000
400	670	4.8 (4)	1.2	1.46	65	115	20,000

(Proposed number of cables)

These tables show that, depending on the detail of the rating calculation, one or two cables less are required for a system with intermittent use.

The derating factor of 0.85 for a number of cables bunched is not applied to the trefoil arrangement, provided adequate spacing for ventilation is allowed. Some authorities advocate a further derating factor for paralleled cables; this allows for the likely imbalance in impedance (particularly reactance) between cables run in an unstructured manner. This factor can be discounted in a trefoil arrangement because it is inherently balanced, provided the lengths of the individual groups can be kept sensibly the same by judicious routing.

It might be thought, from Table 1, that a larger number of smaller cables could reduce the amount of copper required (2 x 90mm^2 instead of 1 x 300mm^2). Apart from increasing the amount of installation and connection work, this might be ruled out from consideration of fault current and protection grading. In the event of a fault, the conductor temperature should not be taken much above 250°C, which might dictate a minimum cross-section.

Possibilities

The possible reduction in cable to transport a given power is up to a third. This is well worthwhile because of the decrease in material cost, the reduction in cross-section of the cable run and hence easier routeing, and the lessening of the complexity of connection into equipment. The problem of connecting a large number of cables to shock-mounted equipment should not be underestimated. Each cable needs to be anchored to avoid mechanical stress on the electrical connection, and spaced from its neighbours to respect creepage and clearance distances.

Similar reductions can be applied to the low voltage system; in the T45 targets would be the feeders from the transformers to the switchboards (2,700A), alternative feeders to load centres, shore supply connections, and switchboard interconnectors (these are not normally closed up).

There will be some adjustments needed to accept this philosophy; cable terminations must be proven satisfactory for the increased currents, and cables must be expected to run very hot to the touch – usually a symptom of a problem. More care must be taken of ventilation; not usually a problem in machinery spaces but a potential risk in false floors or large gland boxes. The use of DC for the propulsion power system could further reduce the burden of cabling.

Conclusions

Consideration of the materials of electric cables and their properties yields substantial opportunities to reduce the cost and impact of a high power electrical system, typically as used for ship propulsion.