Shipboard Power Cable Sizing Methodology

by Ir. Mohammad Adnan Sujan

Ir. Mohammad Adnan Sujan, P.E. graduated from Drexel University Philadelphia, USA in Electrical Engineering (BSc. 1998 and MSc. 2001). He has 15 years of working experience in the engineering industry, ranging from manufacturing plant, electrical power plant, nuclear waste and water treatment process treatment plant to the oil and gas industry, covering the onshore, offshore and Floating Production, Storage and Offloading (FPSO) designs.

One of the most important aspects in the electrical design today is the completion of the interconnection between equipment by the correct/proper selection and use of cables. Depending on the equipment in question, power, control and data transfer protocol become the design necessity in ensuring a high efficiency in power transfer.

In this paper the main discussion will be on the engineering criteria in sizing and selecting low voltage power cables, typically in the range of 0.6/1kV, applied typically for the marine and offshore industry. In the discussion, the design constraints and limitations of usage will focus on the type of cable materials, the core and its insulations used in the harsh and corrosive marine and offshore industry.

We will start with the type of power cables normally selected for the industry, followed by its internal and outer construction materials, factored in the external forces influencing the cable sizing calculation design parameters

No.	Conductor IEC 60228 Classification	Screen	Insulation (Table 1 of IEC 60092-351)	Filler (Multicore cables)	Bedding/Inner Sheath	Armour	Outer Sheath (Table 1 of IEC 60092-359)
1.	Annealed Copper (Cu) or Aluminium (Al) / Aluminium Alloy	Mica / Glass Tape for Fire Resistant	Thermoplastic Polyvinyl Chloride or copolymer of vinyl chloride and vinyl acetate -PVC/A	Non-Hygro-scopic	Thermoplastic PVC (Polyvinyl chloride)	AWA - Aluminium wire armour, used in single-core cables	Thermoplastic compound Polyvinyl chloride or copolymer of vinyl chloride and vinyl-acetate ST 1
2.	Plain or metal coated		Elastomeric or Thermoset Ethylene-propylene rubber (EPM or EPDM) - EPR or halogen-free EPR	Moisture resistant	Low Smoke Halogen-Free Flame Retardant thermoset compound or EVA	SWA - Steel wire armour, used in multi-core cables	Thermoplastic halogen Free SHF 1
3.	Aluminium and aluminium alloy conductors, circular or shaped		High Modulus or Hard Grade Ethylene Propylene rubber – HEPR or halogen -free HEPR			Copper, Galvanized Steel and Bronze Wire Braids	Thermoset compound polychloro-prene rubber SE 1
4.	Circular, annealed copper conductors		Cross-linked polyethylene - XLPE or halogen-free HFXLPE			Aluminium and Galvanized Steel Wire Double Layer Tapes	chlorosul-phonated polyethelene or chlorinated polyethylene rubber SH
5.			Silicone Rubber – S95 or halogen-free - HF S95				Thermoset compound Halogen free SHF 2
6.			Cross-linked polyolefin material for halogen-free cables HF 85				

Table 1: Single Core Cable Material Construction per IEC standards [References 4-8]

and constraints, assumptions, its steady state operation, its resilence and its capability when subjected to the transient operations. The paper will end with the steps taken to do complete power cable sizing calculation and selection analysis and assumptions chosen in the sample calculation. Ship loads can be considered essentials to the personnel on board. This is in addition to the emergency loads applied to ensure safety on-board. Thus, design extreme parameters shall be carefully identified and analysed.

In a typical sizing calculation for the electrical equipment, the novelty approach is to subject the equipment to the operational parameters during its lifetime at any site and installed conditions. By the same token, power cable sizing procedure is standardised to the same principles to ensure cables will provide sustainable operability without affecting its performance during its effective lifetime.

2.0 POWER CABLE CONSTRUCTION

Basically, power cable consists of thin copper (or aluminium) wire, stranded, solid concentric or compacted as per IEC60228 class 2. In the case of emergency uses of the cables, Mica Tape is applied in lieu of the screen, as per the IEC 60331. This type of fire resisting characteristic is defined in such a way that its intended function is to conduct without jeopardising cable integrity under prolonged fire condition, which is limited to 3 hours based on IEC 60331.

Based on Table 1 IEC 60092-351, this screen layer is then insulated with one of the insulating materials. Divided into two main material structures, the first is the thermoplastic compound such as PVC. This thermoplastic material is not well received in the design since it has a low steady state and transient state maximum temperature breakdown limits. Preference (or sometimes specified by the electrical designer) is for the use of a second insulation material, the elastomeric material, better known as the thermo set such as cross-linked polyethylene (XLPE), halogen-free XLPE, ethylene propylene rubber, silicone rubber or the cross-linked polyolefin. It is preferable due to the maximum temperature profiles of the materials to maintain integrity during steady state, overload and short circuit conditions. The XLPE can withstand up to 900C during its steady state operation, the maximum temperature of 1300C for the overload condition, and the maximum cable temperature of 3500C in case of short circuit.

Referring to Table I of IEC 60092-359, as for the case of single core cable, a layer of halogen-free thermosetting compound SHF 2or halogen-free mud-resistant cross-linked compound, SHF mud resistant, is used as the inner covering or inner sheath. This provides mechanical and environmental stresses imposed on the insulated core. Mechanical strength is required due to installation requirements and environmental stress is mainly due to the corrosive and damaging environment. Armour is the choice for providing mechanical protection of the cable for a single core cable. This is normally accomplished by applying either braided tinned copper wire, bronze wire, aluminium wire or galvanized steel wire helically wraps around the insulation. Sometimes, the amour materials can also be of copper, bronze or galvanised steel wire braided or double layer tapes.

For the multi core cables, low smoke halogen-free, non-hygroscopic materials are added to prevent moisture absorption, as well as to provide fills on the multi conductors arranged and grouped together above. Depending on the standards used and applied as references for the project, cores are coded and identified with colours, as example shown below (Reference 10):

One core: Black
Two cores: Blue – Brown
Two cores + earth Blue – Brown – Yellow/green
Three cores: Brown - Black – Grey
Three cores + earth Brown - Black – Grey – Yellow/green
Four cores: Blue - Brown - Black– Grey
Four cores + earth Blue - Brown - Black– Grey – Yellow/green

Five cores Blue - Brown - Black– Grey - Black
Above 5-cores: Black numbers on white base.

Finally, for the outer sheath, referring to IEC 60092-359, Table 1, a mud-resistant, halogen-free thermoset compound, SHF 2, material is applied as the final layer. As standard practice, the colour for the outer sheath is black. In short, Table 1 below illustrates the overall construction and materials of a power cable standardised for the marine and shipboard applications.

3.0 POWER CABLE INSTALLATION REQUIREMENTS

In selecting the best cable for the application, such as for use on the shipboard, the first step is to ensure the cable selected complies with the project requirements. Also refer to the international standards at all times to ensure cables are manufactured and materials used are according to international standards, with design safety margin factored in. The standards to be used are as follows but not limited to, IEC, ANSI, NORSOK, etc. Further analysis involves consideration of the installation requirements such as the installation area ambient temperature and the installation methods applied to the project. In short, the process of selecting the correct power cables, in compliance with standards and requirements, are as follows:

3.1 Identify Project Specific Requirements such as the following, but not limited to:
  a. Specific project design standards
  b. Specific cable construction and materials requirements
  c. Specific manufacturer technology
  d. Special manufacturer tests.

3.2 Identify International Standards to be used such as follows but not limited to:
  a. International Electrotechnical (IEC)
  b. American Standards or ANSI
  c. Local operator standards
  d. Specific local government requirements
  e. Classification bodies such as DNV or ABS.

3.3 Identify the environmental requirements for the applications:
  a. Ambient temperature (°C)
  b. Maximum ambient temperature
  c. Termination point temperature limit
  d. Coldest temperature
  e. Hot spots or presence of heat source such as boilers etc.

3.4 Identify the cable routing and support requirements:
  a. Laid on open or closed perforated cable tray
  b. Laid on cable ladder
  c. Laid against walls
  d. Cables bundled with other cables
  e. Cables installed with spaces between them
  f. In conduits.

3.5 Identify cable installation and pulling requirements:
  a. Cable bending radius
  b. Cable pulling limit
  c. Termination details
  d. Multi cable transit availability.

3.6 Identify the cable load requirements its respective fire resistant properties:
  a. Normal usage (continuous or intermittent)
  b. Standby power application
  c. Emergency usage.

3.7 Identify the cable load requirements its respective installation conditions:
  a. Mud/oil immersion or corrosive resistance
  b. Low smoke requirements
  c. Ozone & radiation resistance

d. Water ingress or moisture resistance
e. Explosion and fire area.

In practice, the worst case scenario of each of the conditions above is configured and selected. This will ensure the size limitations, site ambient, transient operating factors and design restrictions are factored in. In other words, the most extreme parameters of the site ambient and installed conditions will become the threshold for the cable design.

4.0 POWER CABLE ELECTRICAL REQUIREMENTS

The calculation steps here are to ensure cables perform as intended without thermal degradation on its insulation during its lifetime. The steps involved in sizing cables based on the conditions section, are:

4.1 Identify voltage levels for the system:
a. High voltage of the ship (i.e. 6.6kV)
b. Low voltage (i.e. 690V, 440V, 400AC)
c. Very low voltage
d. Control system
e. DC system.

4.2 Select number of phases for AC loads:
a. Single phase
b. Three phase
c. DC system.

4.3 Identify the loads the cables are connected to:
a. Generators
b. Motors
c. Variable speed drives
d. Soft starters
e. Heaters
f. Distribution boards
g. Transformers
h. Uninterrupted power supply.

4.4 Identify project requirements:
a. Cable voltage drop
b. Voltage dip at motor control centre bus bars
c. Harmonics contents
d. Terminals
e. Safety requirements, reflective voltage wave issues
f. Lightning induced voltage.

5.0 POWER CABLE SIZING CALCULATION METHODOLOGY

The following are the calculation steps for power cable sizing.

5.1 Calculate Load Full Load Ampere (FLA) based on the equipment rated apparent Power (kVA) or Real consumed power (kW) or as provided by the manufacturer:

$$FLA(A) = \frac{\text{Total kVA}}{SQRT(3) \times V_{LL}} \quad \text{Eq. 1}$$

$$FLA(A) = \frac{\text{Power (kW)}}{SQRT(3) \times V_{LL} \times Eff \times PF} \quad \text{Eq. 2}$$

Where:
kVA = Apparent Power
kW = Real Power
VLL = Line to line voltage
PF = Power Factor
EFF = Efficiency of the equipment at rated power

5.2 Calculate installed FLA based on Equation 1 or 2 above. In this case, thermal derating factors are applied.

FLA' = FLA x DF Eq. 3
Where DF = AF x GF Eq. 4
AF = Ambient temperature derating factor
GF = Group of installed cable derating factor

5.3 Cable manufacturers or vendors normally provides cable ampacity chart or cable current carrying capacity, for the designer to select the cable from the vendor confirmed ampacity table meeting the requirement of 5.2 above.

5.4 Cable shall be designed to operate in steady state conditions and in the limited time of overload conditions. Effectively, the site and installed ampere rating, I_S (5.2 above) shall be less than that of the rating the circuit breaker rating current of the cable protective devices, I_t. To ensure safe operation of the cable, the selected cable ampere rating, I_N must be greater that the two conditions above. In principle, the ampacity rating must comply with the equation shown below:

$$I_S < I_t < I_N \quad \text{Eq. 5}$$

In addition, the cable let through energy I^2t (A^2s) shall be greater than that of the circuit breaker let through energy selected to protect the cable.

5.5 Based on the selected cable and its estimated length, calculate Voltage Drop during steady state or during motor starting using formula below (Reference 3):

Three Phase Volt Drop:

$$V_{3Ø} = \frac{\sqrt{3}I(R_c \cos Ø - X_c \sin Ø)\,L}{1000} \quad \text{Eq. 6}$$

Single Phase Volt Drop:

$$V_{1Ø} = \frac{2I(R_c \cos Ø - X_c \sin Ø)\,L}{1000} \quad \text{Eq. 7}$$

DC Circuit:

$$V_{dc} = \frac{2I\,R_c L}{1000} \quad \text{Eq. 8}$$

Where:
R_c = Cable AC or DC Resistance of the cable (Ω/km)
X_c = Cable Reactance of the cable (Ω/km)
I = Full load or Starting current (A)
L = length of the Cable (m)
Cos (Θ) = Power Factor (per Unit).

The percentage (%) of voltage drop is then calculated to ensure it meets the limit set by the project requirements.

$Vd\ \% = (Vd / V_{LL}) \times 100$

Eq. 9

5.6 Referring to IEC 60364, the next step involves confirming the selected power cable as a result of maximum short circuit or fault currents. It is a way to check the cable thermal integrity once it is subjected to a high current cable temperature rise and subjected to the maximum short circuit current in a short duration prior to circuit releases either by a circuit breaker or a fuse.

5.7 The calculation focuses on the minimum size of the cable to sustain the short circuit energy that will raise the temperature profile of the cable in a short duration without any thermal degradation and damage. The size shall be sufficient so that the insulation materials and performance are not affected. The formula, captured from reference (3), is given below:

$$A = \frac{\sqrt{i^2 t}}{k} \qquad \text{Eq. 10}$$

Where:
A =Conductor minimum
i^2 t= energy of short circuit (A2 s)
k = Constant from reference (5)

$$k = 226\sqrt{\ln\left(1\ \frac{\theta_f - \theta i}{234.5 + \theta_i}\right)} \qquad \text{Eq. 11}$$

Where:
$\theta f - \theta i$ are the initial and final conductor temperatures respectively.

5.8 Earth loop can be a separate cable or the cable armour to provide a return path for the earth fault current. In our case, the calculation is to determine the maximum length allowable so that the cable impedance is limited to ensure sufficient current for the protection circuit breaker to operate within the required disconnection time period. The formula for the maximum length is given below (Reference 3):

$$L_{max} = \frac{1000V_0}{I_A\sqrt{(R_c + R_e)^2 + (X_c + X_e)^2}} \qquad \text{Eq. 12}$$

L_{max} is the maximum cable length (m)

Vp is the phase to earth voltage at the protective device (V).
IA is the earth fault current required to trip the protective device within the minimum disconnection time (A).
Rc and Re are the ac resistances of the active and earth conductors respectively (Ω/km).
Xc and Xe are the reactances of the active and earth conductors respectively (Ω/km).

No.	Steady State	Transient State
1.	Full load Ampere (FLA) of the equipment @ installed conditions	Short Circuit Current capability (temperature rise)
2.	Voltage Drop Requirements	Inrush Current (Starting Current)
3.	Earth Fault Loop Impedance	High voltage at the terminals due to reflective voltage waveform
4.	Overload condition in which Cable Ampacity is greater than that of cable protective device interrupting rating	Lightning induced voltage (Reference 2)

Table 2: Cable sizing criteria for the shipboard and offshore applications

6.0 SUMMARY

Based on the discussion above, the operational conditions are basically divided into two criteria or scenarios. The first is the cable operation in a steady state and the other is when the cable is subjected to the transient states. Table 2 summarises the criteria of the two operating conditions. For the extreme conditions, the cable intended performance is not affected and the insulation integrity of the cable produces no thermal degradation which can reduce its lifetime and jeopardise safety.

EXAMPLE:

You are to size the power cable, connecting from the existing 400V 50Hz LV switch gear in a 10-year-old DNV certified FPSO to the 250kW three phase motor for the crude transfer pump. The power factor and its efficiency of the motor are assumed 0.8 and 85% respectively. The starting current is about 6.5X the full load ampere. The motor is located outdoors above the main deck and exposed to the environment. The ambient temperature for some location of the routed cable is, at times, as high as at 50°C. It is protected by the air circuit breaker trip rated at 800A. The length is about 200m from the electrical room in the FPSO electrical room which is located adjacent to the main ship bridge. The FPSO is located in an offshore location north of Borneo oil field.

Step 1:

Check the installation based on the site conditions shown in Section 2 above. The finding is given below:

a) The cable must be DNV classification and the project requirement includes XLPE insulated, armoured and PVC outer sheath.
b) The ambient temperature is 40 degrees Celsius and highest can be at 45 degrees.
c) The cable will be routed with other cables, bundled with other cables.
d) It is for normal process use.
e) It shall meet the requirements of mud resistant and low smoke zero halogen type cable.

Step 2:

Check the electrical requirements based on conditions shown in Section 3 above. The finding is given below:

a) It is LV application 400V AC 50Hz and thus 0.6/1KV insulation type cable is selected.
b) It is three phase motor with separate earthing cable.
c) It must meet less than that of 5% voltage drop at the motor terminal during normal operation.

Step 3:

Calculate the FLA using equation 2 above. The finding is given below:

FLA = 531A
Where KVA = HP x 746 Equation 5
Project requirement may include a minimum size of 25% greater than that of the FLA. The finding is given below:
FLA'= 651.31A

Step 4:

Select power cable that meets the requirements above, from technical data provided by the vendor. Example,

a) 2 x 1C x 240 mm sq (1044A) **or**
b) 3 x 1C x 185 mm sq (1332A)

Step 5:

Calculate the FLA applying derating factors, based on Section 4.2 above. The finding is given below:

A. 2 x 240 mm sq: FLA' = 2 x 522 x 0.95 x 0.78 = 773.6A
B. 3 x 185 mm sq: FLA' = 3 x 444 x 0.94 x 0.78 = 987A

AF = 0.94 & GF = 0.78

The cable above is selected based on the Section 3 above. In addition cost control, availability and specific project requirements may be considered.

Step 6:

Calculate the overload conditions shown in Section 5.4 above. The finding is given below:

$531A \le 800A \le 987A$

Thus, cable (B) meets the conditions of equation (5) above and is selected.

CAUTION: Make sure to also check the space for routing, transits, conduits and airways, tight areas, termination, and bending possibility.

Step 7:

Calculate voltage drop using formula shown on Section 5.5. The finding is given below:

=183.94((.128 x 0.8) + (.096 x 0.6))/3
= 29.43 / 3 = 9.8V

Since it is 3 parallel run per phase, then at each run, the drop is 10.8V.

Voltage drop during motor starting, given that:

- $I_{starting}$ = 6.5 times FLA
- PF is assumed at 0.3

= 3452[(.128x 0.3)+(.096x0.954)]/3
= 9.92%

So, the voltage drops are acceptable as during steady state, is about 1.03% and during starting the % drops is 9.92 %

Step 8:

Then check the cable insulation integrity against the possible short circuit current or faulted current maximum at the cable itself. In this case, equation (10) is applied.
Assuming that Ik is the prospective short circuit current of 25kA, the protection set at 1 sec and by reference (9), with the operating and limit cable temperatures at 250 and 90 degrees C respectively, the temperature rise constant is:

k = 143

Therefore, the minimum size of the cable to sustain the impact of this maximum short circuit current is

A = SQRT [(25000^2) x 1]/143
= 174 mm^2

For a 650A earth fault protection with a 3-second opening time, the minimum size of the cable is given below:

$$A = SQRT\ [(650^2) \times 3]/143$$
$$= 7.8\ mm^2$$

The selected cables can handle the short circuit thermal transient effect above.

Step 9:

For a separate earthing used for the load, calculate earth fault loop impedance to determine the maximum length for the cable for the earth fault protection Equation 11 above.

Assuming that the earthing cable is 70mmsq cable, taken from equation 12 above, the finding is given below:
Lmax = **454m**. ■

REFERENCES

[1] ABB SACE, technical Guide, Electrical installation handbook Protection, control and electrical devices, 6th Edition 2010, Bioni, 35-34123 Bergamo Italy

[2] C. Gomes and M. Z. A. Ab Kadir, Protection of Naval System against electromagnetic effects due to lightning, Progress In Electromagnetics Research, Vol. 113, 333{349, 2011, Centre of Excellence on Lightning Protection, Department of Electrical and Electronics Engineering, Universiti Putra Malaysia, Malaysia

[3] http://www.openelectrical.org/wiki/index.php?title=Cable_Sizing_Calculation

[4] IEC 60092, Electrical Installation in Ships,

[5] IEC 60228, Conductors of insulated cables

[6] IEC 60364, Electrical Installations of Buildings

[7] IEC 60502, Power Cables with Extruded insulation and their accessories for rated voltages from 1kV (Um = 1,2 kV) up to 30kV (Um = 36kV)

[8] IEC 60724, Short-circuit temperature limits of electric cables with rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV)

[9] LS Cable, LS Medium & Low Voltage Power Cables, 0.6/1kV~18/30kV According to IEC 60502, 61034, 60754

[10] Sizing conductors and Selecting protection devices, Power Guide 2009, Book 04, legrand©

[11] Universal Cable (M) Berhad, Offshore Marine and Shipboard Cable catalog

IEM DIARY OF EVENTS

Title: One-Day Course on Development of Precast Concrete Technology (Re-scheduled from 5 August 2015, Wednesday)

17 September 2015

Organised by : The Young Engineers Section - Graduates & Student
Time : 9.00 a.m. – 5.00 p.m.
CPD/PDP : 6.5

Title: 2nd Mentors Workshop 2015 - "Log Book Training Scheme - Guidelines for Mentors"

19 September 2015

Organised by : Standing Committee on Examination and Qualification
Time : 8.00 a.m. – 1.00 p.m.
CPD/PDP : 3.5

Kindly note that the scheduled events below are subject to change. Please visit the IEM website at www.myiem.org.my for more information on the upcoming events.