Comparative Assessment Between LV & MV Electrical Power Systems & Equipment for Marine Applications

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Synopsis

As we tend towards more electric power distribution networks including distributed energy resources (DERs) which are increasing in terms of power capability and requirements. The design of the electric ship power and distribution system follows suit with the added challenge of achieving smaller footprint on islanded power distribution networks. These challenges are namely, equipment and conductor sizes, including the associated infrastructure such as interconnecting power cables, copper busbars and the associated supporting installation equipment including cable trays and ladders. Additionally, noise & vibration, shock, and other environmental factors along with the associated forces during fault events such as short circuits and the insulation challenges particularly on MV system must be considered.

The selection criteria for using MV or LV technology is therefore non-trivial, and not limited to only the best technologies available at the time of consideration, but, to other considerations including cost, technology readiness level (TRL) of equipment, power density and feasibility of installation and integration among some of the overall considerations.

A clear understanding of the advantages & disadvantages of LV and MV technology leads to the design of better systems that can future-proof the capability of the electric grid and enables the use of clean energy at larger scale using sources such as hydrogen or similar fuel cells and batteries, which are modular and well suited for power stages inherent in converter technologies. A novel solution using an LV DC to / from MV DC converter topology patented by GE-PC, allowing greater flexibility in MV-DC systems, while maintaining a smaller footprint is presented in this paper.

This paper aims to examine the various factors involved in specifying an electrical power system with supporting power equipment holistically and how these factors can affect the decision based on the use of MV or LV technologies.

Keywords: BESS, Energy Storage LV, MV, Marine Systems

1. Introduction

The requirements for marine, offshore and naval vessels are extremely diverse whilst coupled with customer parameters, there is a great design variety that should be reviewed, optimally selected, and matched to system specifications. In some cases, customers seek guidance on the most appropriate options and design choices partly covered herein.

Voltages up to & including 1000Vac or 1500 Vdc are known as low voltage (LV) systems. In maritime practice for ships, any voltage above LV is termed high-voltage (HV) system. However, voltages up to 35kV AC (IEC) are defined as medium voltage & above 230kV AC (IEC) are called high voltage in land-based practices.

Any voltage above LV is referred to herein as MV. The question, though, is which is better, LV or MV? Like most engineering questions, not only does the cost and complexity need to be considered, but also the differences in each equipment in the full context of the application.

This paper intends to start from ***first principles*** and provide commentary on how these choices affect a system, to help the reader to conclude on which voltage level to select for system design.

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2. Current & Voltage as factor in System Design

2.1. Conductor current characteristic

IEC 60092-354 (Table A.1) provides recommendation on cables, based on which
Table 1 is derived.

The voltage-drop, insulation temperature limit, thickness, thermal conductivity, and air convection, i.e., physical cable installation (bending), bunching factors and temperature should all be duly considered.

It is evident from
Table 1 that selecting MV over LV cable has significant advantage in terms of requiring less conductor volume for the equivalent power level.

2.1.1. ***Cable Losses***

Losses are predominantly caused due to resistance and are a function of current. Ref. *Eq. 1*

$$Conductor\ Losses\ \alpha\ I^2R \qquad Eq.\ 1$$

Losses are an important consideration in system designs since these drive-in onerous requirements in terms of cooling which can result in heavy, noisy, costly, and high maintenance equipment to remove losses via HVAC, indirect or direct air or water cooled systems.

Considering a 3-φ - 1000 kW system at unity power factor (pf), the currents are as shown in
Table 1

Table 1 :Comparison of LV and MV cable based on 1000 kW system

Description	MV (4160 V)	LV (690V)
Current (Amps)	139	837
Closest Cross Section (mm^2)	(1 x 70)	(2 x 185)
Weight of copper (kg/m)	(~4 kg/m)	(~2 x 10kg/m)
Losses (kW) for 25 meters of cable.	0.4	2.4 [1] / 3.1 [2]

[1] Copper / [2] Aluminium. **Note** as of July 2022 Copper and Aluminium raw material cost £6 and £2 per kg respectively.

Overall vessel cabling will be orders of magnitude greater than 25 m, hence it follows that efficiency gains could be achieved through the selection of MV over LV for high power large vessels.

There is a natural limit for 690 Vac$_{rms}$, or indeed high current systems due to the commercial availability of protection equipment. Typically, for 690 Vac$_{rms}$, circuit breakers are available up to 6300 A$_{rms}$ meaning 690 Vac$_{rms}$ is only viable up to approximately 7.5 MW based on an individual feeder. These commercially available breakers are also limited to approximately 120 kA fault current on LV systems. Beyond this you are forced to higher voltage systems due to practical considerations in terms of conductor sizing and fault management. Figure 1 shows an example of a 4000 A$_{rms}$ 690 Vac$_{rms}$ switchboard section showing multiple multi core cables terminated to the section busbars resulting in a large installation space, complex, time consuming installation and onerous maintenance due to the necessity of period inspection of the terminations.

Figure 2 shows a 1250 A MV cable installation, whereby special attention needs to be made in relation to the surrounding area and termination detail to prevent discharge between cables damaging insulation thereby requiring the use of dedicated MV cable termination kits installed by duly trained personnel.

High power LV and MV systems demand high currents which introduces strong magnetic fields that need careful management during operation and fault scenarios with respect to conductor support and bracing, eddy currents introducing localised heating and instrumentation, for example core balance and phase current transformers placement within magnetic fields and the influence they may have on the accuracy of the measurements. Techniques are available to manage this such as cable transposition and lay-up applicable to both

LV and MV systems, however this is more challenging to implement on MV due to constraints imposed by cable termination and stress grading.

Figure 1–LV Switchboard Section (4000 A 4 MW)

Figure 2-MV Cable Termination (1250 A 7.6 MW)

This is not the holistic story as the cost of insulation related to MV systems may make it expensive and non-viable over short distances, or where space is limited. Additional factors to consider are electric field strength (V/m) and magnetic field strength (A/m), again both important factors due for consideration when designing appropriately rated and fault tolerant systems with limited space and potentially onerous requirements in terms of human factors, noise & vibration, shock, EMC, and vessel signatures.

2.2. Voltage v Insulation

The dielectric strength of the insulation material is measured in “volts per mm’’. So, it follows that MV will have thicker insulation requirement compared to its LV counterpart, however not proportionally increasing due to considerations later presented. Hence the increase in the cost of material and fabrication (Figure 3).

Above normal room temperature the dielectric strength of an insulation material is approximately inversely proportional to the absolute temperature; below room temperature the dielectric strength is substantially independent of temperature change.

Mechanical loading has a pronounced effect on dielectric strength as the stress may introduce internal flaws which serve as breakdown paths. Therefore, mechanically loaded insulators may show substantially reduced values of dielectric strength compared with unstressed components. The dielectric strength of the material is influenced by the fabrication process e.g. the flow lines in a compression moulding or weld lines in an injection moulding may serve as paths of least resistance to leakage currents reducing the dielectric strength; minute flaws in a plastics insulator may reduce the dielectric strength to one-third the normal value.

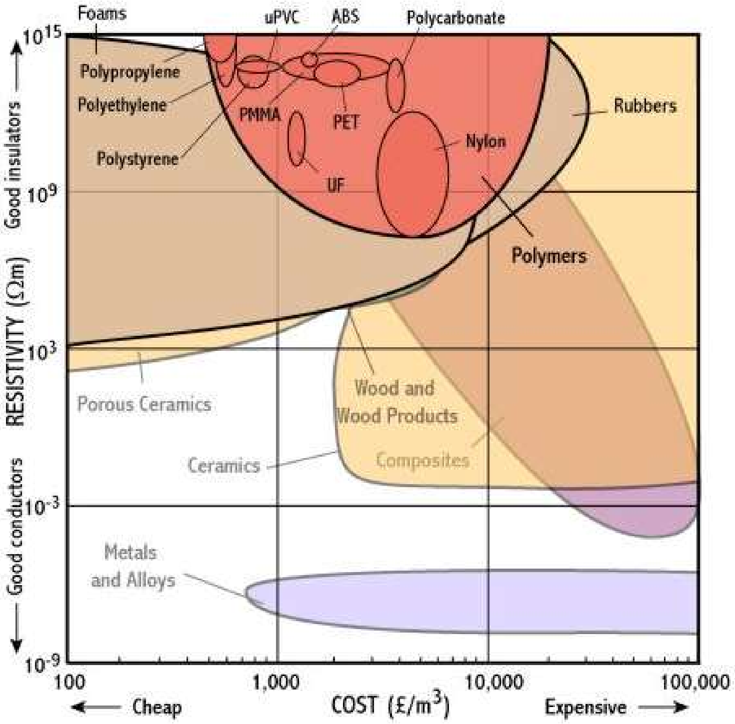

Figure 3: [1]*Cost of typical polymers used in insulation* [1]

3. Equipment-wise breakdown

3.1. Implication of MV & LV on Switch Boards

There are significant differences to consider when designing switchboards. They are governed by:

- IEC 61439 – for systems up to and including 1 kV ac and 1.5 kV dc
- IEC 62271 – for systems from 1 kV ac up to 52 kV ac

The creepage and clearance as defined in various class rules and standards is one such factor. Even though MV benefits from lower conductor content, i.e., volume and weight, the overall equipment volume maybe comparable, or larger to LV system due to switchgear and other clearance requirements.

LV systems are preferable at lower power, but as the powers increase, LV rating capabilities beyond ~7.5 MW per feeder is no longer viable and MV systems are preferred in part to the reduced fault capacity.

For LV systems, the fault contribution can quickly increase when considering numerous large prime movers connected to the power distribution system, take for example, 4 prime movers with a rating of 2.5 MVA each, and 13% impedance, yields 64 kA compared to 10.7 kA for the equivalent system rated at 4160 Vac.

At similar power levels for MV and LV systems, there are the advantages and disadvantages of both types:

LV Switchboard

- Higher fault rating on the switchboard, this could restrict the available type tested solutions.
- Higher current, therefore larger bus bars for comparable powers.
    - Higher losses to air, therefore affecting radiated heat (and increased HVAC loading).
    - Larger busbars to manage the current, therefore increase in volume and weight.
- ACB weight compared with VCB (MV System circuit breaker), ACB is lighter.
- Arc free design, also not mandatory to be tested for internal arc containment.

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[1] This is data from 2002.But the general trend holds good.

- Depending on the form for segregation, this will affect switchboard length.
    - Form 4b, LV switchboard longer than MV.
    - Form 2, LV switchboard shorter than MV.
- LV circuit breaker is lower cost than MV (LV breakers typically incorporate protection functions).
- MCCBs can be used for down stream distribution, current limiting options are available.

MV Switchboard

- Lower fault rating.
- Lower full load current
    - Lower losses to air.
    - Smaller quantity of busbars, therefore a reduction on weight.
- Switchboard meets LSC2B for segregation, compared to form 4b this could be less.
- Internal Arc Testing is mandatory.
    - Arc gas management to be type tested and exhausted to a safe area.
- Corona discharge is a possible by-product, therefore, correct cabling, terminating, and routing to be adhered to.
- Required MV trained Suitably Qualified Experienced Personnel (SQEP)

3.2. Implication of MV & LV on converter

An MV converter is often physically larger than a comparable power LV configuration up to approximately 6MW. In part, this is because internal clearances must be greater to prevent arcing faults (like switchboards). Additionally, the components related to the voltage level are typically larger in the MV VFD, requiring more room to mount and maintain, although the MV converter may be lighter.

It should also be noted that energy storage devices such as fuel cells and batteries typically operate at LV, the maximum commercially available, marine certified battery available is 1200 Vdc. Methods are available for modular battery sources, as multiple battery cells can be used to build up the voltage, but this is ultimately limited according to the rated insulation.

MV converters are generally used for high power applications. However, the biggest challenges relate to the losses in power transmission, supporting infrastructure and equipment availability and the availability of high power on demand at short notice i.e., high power pulsed loads. Essentially, as the load current increases, so do the losses - requiring larger conductor cross-section area for the same operating temperature. Opting for a higher voltage allows the same power flow at reduced current noting power is a product of voltage and current.

A simplistic view would be that an MV converter has a higher power capability than LV, thus generalised pros and cons apply with respect to build, manufacturing, operation, and installation. This not the whole story – as various PWM strategy can be used to exploit the full potential for each voltage level. [2]

It should also be noted that LV converters below approximately 3 MW will be more economical due to their commercial availability, whereas the MV equivalent is likely to be more expensive as these converters become more specialised and the volume benefit is lost.

3.3. Implication of MV & LV on Electrical Machine.

Permanent magnet machines (PMM) are gaining traction in applications for marine propulsion in applications of Power Take-Off (PTO) and Power Take-In (PTI), but the induction machine is still popular due to the relative costs, simplicity, and mainly known failure modes and reduced reliance on rare earth materials.

Machine windings tend to be wound with round enamel-covered copper conductors; this type of winding is called random-wound or mush-wound. MV motors, with voltages up to 13.8 kV or even higher, are wound with rectangular cross-section copper conductors with enamel or mica tape insulation depending on the voltage level and manufacturing technology used. MV machines are generally made using a winding type known as form-wound coils. Higher voltages are bar wound with rectangular section copper conductors which may have an enamel coating or with taped insulation.

Form-wound coils are individually insulated and formed to precise dimensions and so are more expensive to manufacture. Thicker insulation is required at higher voltage levels as explained in 2.2. and the amount of copper required is increased as explained in 2.1.

At 5kV and above the insulation must also resist electric discharge and this generally means that the insulation contains mica, usually in fine flakes, with a resin binder. The binder is normally a thermosetting resin using either pre-impregnated insulating tapes (resin-rich) or vacuum impregnation technology.

LV machines are usually "mush" wound and being LV there are normally only 1, 2 or 3 turns per slot and the end connections are designed so that the voltage between conductors in the slot is minimised. The position of conductors within the slot of a mush-wound machine can be relatively random and true inter-conductor voltages can be difficult to predict; with MV machine windings this randomness is eliminated, and the highest delta V is restricted to between turns.

Depending on the country, industry, and specific user, the philosophy of where to use commercial LV and MV motors differs greatly, although commercial machines have wide availability in the LV and MV ranges, whereas higher power LV machines tend to be more bespoke and specialist according to the specific application. MV motors are also available at lower powers for specific applications [3].

3.4. Implication of MV & LV on Harmonic Filters.

Harmonic filtering tends to be a bespoke design, as this is used to mitigate the harmonics due to polluting equipment of various components in the power system-namely power converters and generators.

Every topology, irrespective of the voltage level is unique, so attention should be paid to this component when designing into the holistic system, including the requirements of class societies in terms of the harmonic magnitude and frequency.

MV filters are generally very large due to creepage, clearances and the insulation properties necessary. MV filters are infrequently employed in Marine systems due to this. Other mitigations are usually adopted such as 12 or 24 pulse configurations. LV systems harmonic filters tend to be smaller, and for larger powers can result in heavy systems due to the associated ratings of the passive components. It should also be noted that MV converters tend to operate at lower switching frequencies compared to LV converters and hence further associated impacts on filter sizing.

So, in case of filters, the engineering and technical appropriateness drives the design decisions based on the topology selected, however, MV filters will generally be larger than LV filters, but LV filters although being smaller, may be more densely populated due to creepage and clearance, but may well be heavier. It should be noted that the use of LV filters is also rare since LV harmonic mitigations typically use 12, or 24 pulse configurations, or Active Front End (AFE) converters.

3.5. Installation Considerations Between LV & MV.

LV systems are governed by rules & guidelines which are mostly in line with the land-based counterparts. These are not onerous and can be easily managed and achieved.

However, for MV installations, the rules & guidelines and required SQEP can be very prescriptive resulting in higher upfront investment costs to comply.

The above duly considered, both LV and MV systems present significant danger to life if safety precautions are not followed. MV systems require specific training. MV and LV systems can present significant arc energy and equipment must be designed appropriately to manage short circuit events. LV systems typically have lower protection against arc faults than MV systems, where MV systems are required to have been tested to prove safety under arc fault conditions.

This necessitates, not only specialist training, but also specialised equipment to be used, hence further driving cost up of MV when comparing to LV systems. [4]

Maintenance is another consideration, as this can impact the lifecycle cost of the system. **Error! Reference source not found.**. clearly shows the requirement & frequency for MV is more demanding compared to LV even when considering just one component.

Table 2 :Sample maintenance schedule of circuit breakers. [5]

Moulded Case Breakers (480 V)		**Low Voltage (600 Volts V and Less 480 V Draw Out and Fixed Air Circuit Breaker**		**Medium Voltage (601–15 kV Rated) Air and Air Blast Breaker**		**Medium Voltage (601–15,000 Vac) Vacuum Breaker**	
Maintenance or Test	**Target Interval**	**Maintenance or Test**	**Target Interval**	**Maintenance or Test**	**Target Interval**	**Maintenance or Test**	**Target Interval**
Exercising by hand	6 years	Preventive maintenance and inspection	3 years	Inspection	Annually	Record operations counter	Monthly
Routine Maintenance Tests	6 years	Insulation test	5 years	Preventive maintenance	3 years	Inspection	Annually
		Overcurrent fault trip testing	3 years	Overcurrent trip settings and testing	3 years	Preventive maintenance	3 years
				Contact resistance measurement	3 years	Insulation test	3 years
				Breaker timing (Motion analyser)	3 years	Contact resistance Measurement	3 years
				Insulation test	3 years	Breaker timing (motion analyser)	6 years

3.6. Commentary of different architectures.

3.6.1. ***Current Architectures***

Current AC architectures are well established and have the building blocks available to facilitate numerous configurations in support of applying DC storage, or power generation to the wider distribution network. For example, DC-AC and DC-DC converters are available and well proven allowing battery systems typically operating at approximately 1000 Vdc to be connected to either AC or DC LV distribution systems.

The fault management of these systems needs careful consideration as the inclusion of batteries with low internal impedance can very quickly combine resulting in very large fault currents that become difficult to manage.

As previously mentioned, several commercial-of-the-shelf (COTS) LV converters are available, and couple effectively to an LV converters DC bus noting these are typically 1100 V dc, closely matching available battery solutions, but the battery voltage drop during heavy loading and charge / discharge should be considered.

MV-DC architectures are limited by the commercially available products. Bespoke options are available in niche sectors, but these are costly and low TRL. Generally, DC marine system architectures are limited to LV systems with high power MV systems opting for AC solutions.

3.6.2. ***Future Offshore Architectures***

To optimise capability and efficiency in the Offshore, Marine and Naval sectors as demanded by the future green and compliant ships targeting net zero emissions, these will be driven further towards electrification, like the automotive sector. One can see the significant gains in performance, capability, and green credentials of, for example a modern typical electric car verses its internal combustion engine counterpart. That said, not many cars are required to undertake the typical journey and carry payloads associated with marine vessels so perhaps an unfair comparison, nonetheless, electrification is key.

Larger, more capable, and powerful vessels typically employ MV systems and as a result the building block availability will be limited, and not as diverse as those available at LV. If, for example alternative energy needs to be applied at MV, this will typically be derived from low voltage sources such as batteries and / or flow cells using LV converters and stepped up to the MV system via transformer(s). An alternative approach is proposed whereby the energy storage could be coupled direct to the bus of a MV converter using modifications to commercial converters. In the case of active front end (AFE) propulsion, this could also be connected to the propulsion 'bus' and PTO applied to supply service loads.

The topology proposed can facilitate the generation of high voltages from low voltages based on the number of stages included in regular boost converter configurations, i.e.

$$Vo = \frac{n \times Vin}{1 - D} \qquad \textit{Eq. 3}$$

Using the equation in *Eq. 3* with a 1000 V dc source and 0.6 duty ratio yields the following results for n levels:

Table 3 - Vo dc vs n levels

n	Vo dc
2	5 kV
4	10 kV
6	15 kV

A 3.3 kV ac inverter usually has a DC link voltage of approximately 5 kV dc which could be achieved using a 2-stage topology with a duty ratio of 0.6, with the topology presented in Figure 4

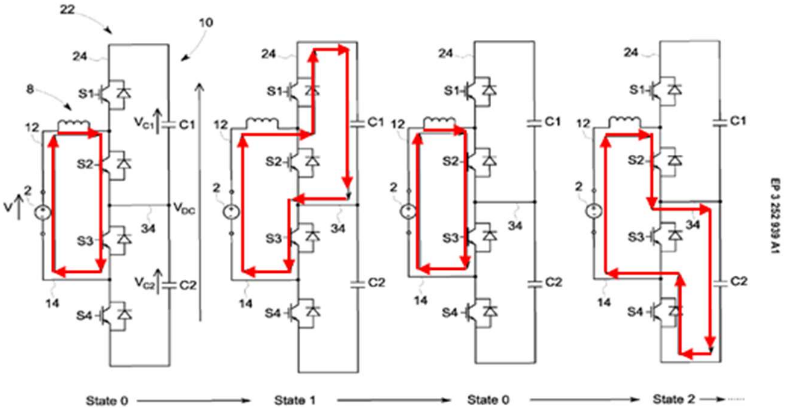

Figure 4 - LV-MV DC/DC Converter (GE Patent 285521-EP-1)

3.3 kV / 4.16 kV systems have been widely employed and may potentially offer an opportunity for exploiting higher power systems where LV proves to be challenging or prohibitive, thereby facilitating the future, more powerful vessel, which is more efficient, with reduced emissions, whilst having options for operation without carbon-based fuels. The option for an LV-MV DC/DC based converter may provide another building block in the arsenal of tools to make the future electric grid more viable in future advanced architectures.

4. Conclusion with BESS as example using the commentary as set above

It can be seen from the body of this paper that the choice of LV and MV selection is non-trivial, and the paper aims to address some of the considerations necessary, but these are by no means complete due to the limited word count of this technical paper. Many other factors require consideration, and it is essential for a close and co-operative relationship between suppliers, shipbuilders, and customers to ascertain achievable and unachievable solutions based on current technologies, costs and project timescales, and where low Technology Readiness Level (TRL) is applied, these are appropriately managed and de-risked prior to deployment.

The selection of LV or MV solutions is still driven largely by the application and associated power requirements with a natural breakpoint between LV and MV of approximately 4.5~7.5 MW, where at 690 V ac the copper cables required to support this are significant over relatively short distances. Over longer distances this clearly would be even less viable. There is no definitive answer as to the selection of LV over MV or vice versa, but technologies are becoming available that facilitate hybrid solutions, i.e. the adoption of LV sources to MV systems and also DC at LV is enabling the fault level constraint to be changed by different protection techniques such as fuses and/or IGBT based protection.

Innovation is a certainty. Thus, leading to new options becoming available and the traditional mindset adapted to LV alternative energy solutions may in future tend towards MV solutions with the building blocks available to facilitate this, i.e. the ability to utilise LV energy sources such as fuel cells and batteries in MV systems thereby achieving lighter, more environmentally friendly, more capable and powerful platforms that have flexible future options and offer performance gains, noting that LV systems already benefit from these gains albeit to limited power capabilities.

Future platforms will also become increasingly complex, requiring more future SQEP and talent that is becoming increasingly more challenging to fulfil requiring a grass roots approach to growing talent for the future to support these future technologies and platforms.

5. Acknowledgements

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