Design of Zonal Electrical Distribution Systems for Ships and Oil Platforms: Control Systems and Protections

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***Abstract*—Complex energy vessels such as large platforms or drillships require more efficient use of electrical power. As shipboard electrical systems become larger, problems and limits arise with the ac distribution architecture. Hybrid ac/dc onboard distribution systems are today available, which provide higher efficiency and redundancy. IEEE Std. 1662, 1709 and 1826 set technical rules and recommendations for the design of hybrid ac/dc shipboard electrical systems. Among these, zonal electrical distribution systems (ZEDS) are considered a next technological evolution, as they provide optimal power sharing (and energy storage) along with high reliability.**

***Index Terms*—Marine power systems, power electronics, zonal electrical distribution systems.**

I. Introduction

COMPETITION in the marine sector imposes changes in the ships power systems. In particular, in the modern integrated power and energy systems the density of power electronics converters is continuously increasing. As an example, in actual large ships with electrical propulsion and ac distribution up to 85% of power is delivered to users through power electronics converters. This rate increases up to 100% in the case of integrated dc distribution systems. In this regard, zonal electrical distribution systems (ZEDS) are the most advanced ones. They can be structured in a modular way in order to provide optimal power sharing (power is controlled and exchanged between zones) in a reliable way (disturbances cannot propagate between electrical zones as they are decoupled by power electronic converters). As an example, IEEE Std 1709 [1] provides a notional high performance medium-voltage dc (MVdc) ship system design (Fig. 1), aimed at maximizing the

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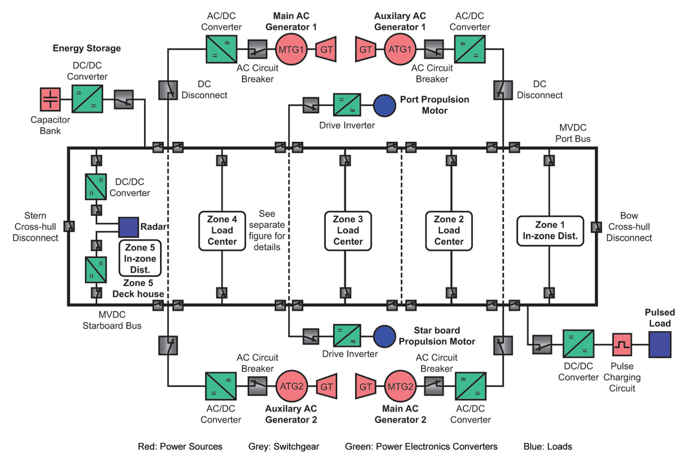

Fig. 1. Notional high performance MVdc shipboard system [1].

operational capability even under extremely adverse conditions. This can be achieved thanks to the zonal architecture, which allows to supply vital loads continuously from either port or starboard buses, and to achieve a split-plant configuration by means of cross-hull disconnect switches.

In ZEDS architecture, the power system dynamic response to load variations, generation variations, and reconfigurations (in general "transient disturbances") is given by power converters' coordinated behavior, which depends on the following: 1) ZEDS control system architecture (normal operations), and 2) ZEDS protections (including conventional and static devices) intervention characteristics (fault operations). ZEDS coordinated control system (e.g., voltage control, power sharing, etc.) behavior depends on different design choices, i.e., a) hierarchical control, b) information and communications technology (ICT) infrastructure for controlling the dc grid, c) filters, in relation to power quality requirements and system stability, and d) control dynamics. On the other hand, ZEDS fault protection affects both the system and the personnel's safety. Therefore, a comprehensive fault management approach must consider both these issues, which are naturally intertwined.

This article reviews the context of control system architectures and fault protection capabilities of ZEDS on ships, with particular reference to complex electric ships and oil platforms. IEEE Standards applicable to ZEDS control and protection

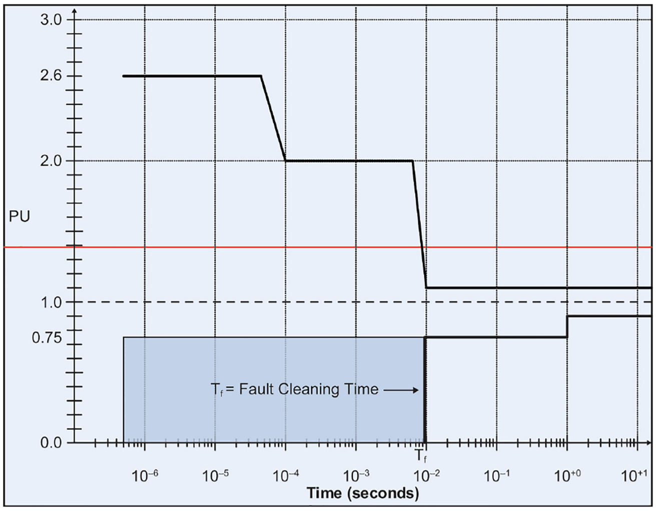

Fig. 2. MVdc voltage tolerances worst case envelope [1].

systems design and evaluation are considered, making precise references to technical sources and applications, to provide a comprehensive technical framework. The article is organized in sections: I. Energy specifications of new electric ships/platforms endowed with ZEDS; recommended design of ZEDS, mostly focused on relevant integration issues such as II. voltage/power controls, III. protections for dc faults and electrical safety, and IV. ICT requirements.

II. Existing IEEE Standard and ZEDS Design Guidelines About Voltage/Power Controls

This section is aimed at defining the practical engineering "guidelines" for designing voltage/power controls on ZEDS. Such recommended practices on ZEDS control are obtained by consulting several IEEE Standards (1709, 1662, 1676, and 1826). In the following, each standard will be reviewed in regards to the onboard dc voltage/power control. Moreover, the paramount concepts of dc microgrid and ZEDS are here given, to provide additional remarks on the management of complex energy vessels.

A. IEEE Std 1709–2018

This standard [1] provides the recommended practice for 1 to 35 kV MVdc power systems on ships. Therefore, it constitutes the first source to be considered for designing onboard control systems and setting related requirements. As expressed in the title, the standard discusses MVdc distribution systems, where the fast switching of newest power converters guarantees an improvement of power flows, especially during transient and emergency conditions. This aspect is the first to be taken into account when discussing the control of MVdc systems. Second, the communication among all power sources and loads allows to optimize the power flow, while maximizing the continuity of service. Thus, fast switching and communication enable the control performance improvement.

For what concerns voltage control, Fig. 2 provides the worst-case envelope for MVdc voltage tolerances. This curve deserves attention, because it is the base on which the onboard voltage control has to be designed. Particularly, the dynamics requirements can be defined in accordance with the last graph, therefore a properly controlled power converter should ensure an output voltage transient within the highlighted limits. In this regard, it is important to highlight the definition of power quality (PQ), which is the compliance with specified voltage tolerances (Fig. 2) and voltage ripple (i.e., RMS value smaller than 5% per unit considering also load-induced noise). Besides the above-depicted conventional requirements, the power converters control has to be designed for assuring both small and large system stability, using either time or frequency domain criteria for providing its assessment. Moreover, it is important to remember the destabilizing effect of high-bandwidth constant power loads (CPLs), whose presence can impair the system stability. In the last years, several studies have been proposed for analyzing the CPL behavior [2], [3], while others have suggested control techniques to restore a stable behavior after perturbations [4]–[6].

Taking into account the importance of system stability, the IEEE Std 1709 [1] suggests the following steps for its assessment: 1) Identify operating points where small-signal stability is to be maintained; b) define a stability metric; c) develop a time-domain model for the MVdc power system; d) define steady-state operating conditions and operating points; e) build a linearized average value model for the selected operating conditions; f) build time-domain simulations to test small/large perturbations; and g) review system dynamic response.

Another important control in a shipboard power system is the one aimed at managing the onboard power [1]. During normal operating conditions, such a control system is able to properly configure the power system for guaranteeing the balance among used and produced energy. This, and the consequent power sharing among the sources, can be ensured in two different ways, namely, 1) coordinated voltage/current control and 2) droop control. In the first case, a single power converter on the generating side is committed to impose the dc bus voltage, whereas the other generating converters regulate the dc currents. Instead, in the second case a conventional droop function can be implemented to share the power among sources, by means of proper resistive coefficients set in the dc voltage control loop of each generating system. In critical conditions, the energy storage systems (ESSs) can support the shipboard grid during power imbalances or generators overspeed. The ESSs can work independently or in coordination with the power management system (PMS). The latter plays a crucial role in case of interruptions, where the dynamics for controlling the power is of paramount importance, both in short-term (few seconds) and long-term (minutes or more) interruptions. Finally, the loads can be voluntarily disconnected (i.e., load shedding) for restoring the onboard power availability.

As a matter of fact, the complexity of MVdc power systems (IEEE Std 1709) leads toward the installation of smart power electronics systems, like power electronics building blocks (PEBBs) [7]–[9]. The following subsections are therefore

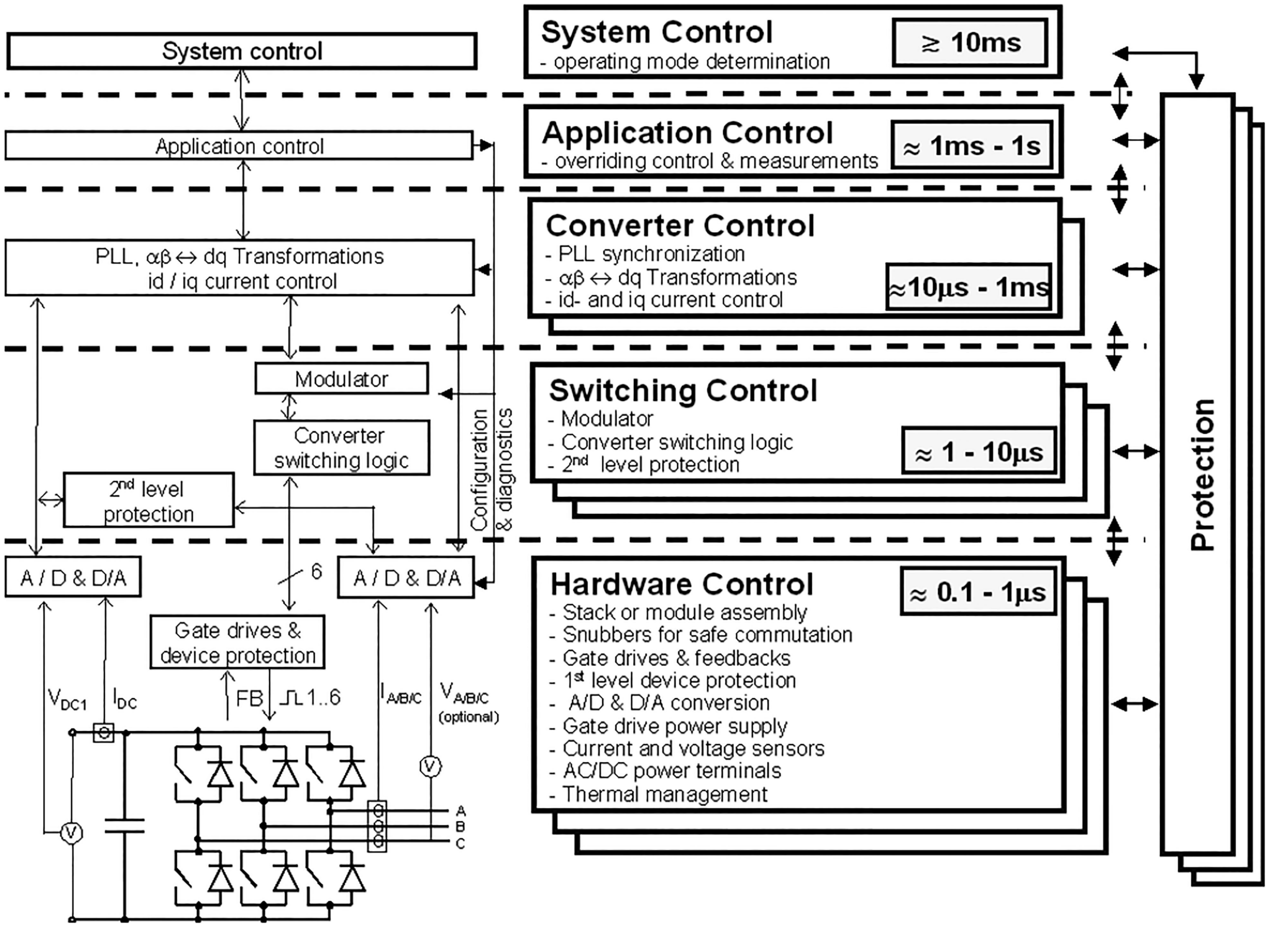

Fig. 3. PEBB hierarchical control architecture [11].

addressed in explaining the PEBBs control architectures (IEEE Std 1662 and 1676), whilst their application on ZEDS will be described by means of the IEEE Std 1826.

B. IEEE Std 1662–2016 and IEEE Std 1676–2010

The PEBBs are recognized as actuators [7]–[9] for achieving the voltage/power controls on ZEDS. During the last years, a great effort has been spent in defining PEBBs. Their main characteristics are reported in IEEE Std 1662–2016 [10] (Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems) and in IEEE Std 1676–2010 [11] (Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems). In detail, a PEBB is not only an electronics actuator but also it represents a wider concept, whose hierarchical architecture is shown in Fig. 3. In this scheme, it is possible to observe the main elements (left side) constituting a PEBB together with the control layers (right side). Moreover, the important interface to protection is also highlighted. Regarding the elements, several blocks can be pointed out, namely, power converter, measurement equipment, A/D-D/A blocks, modulator, switching logic, protections, and so on. The PEBB hierarchical structure is particularized in the following for understanding the control capability [10], [11].

1) System Control Layer (Sys): The upmost layer is responsible for determining the operating mode (thus system mission and power electronics duties) by receiving status information and sending control loop settings. For this layer, the suggested time constant is higher than 10 ms, while the asynchronous communication with lower layers is obtained by fiber optic Ethernet (TCP/IP protocols).

2) Application Control Layer (App): For fulfilling the system mission, App layer manages (time constant from 1 ms to 1 s) the converter control layers, which are conveniently regulated for behaving as equivalent devices (i.e., controlled current source or controlled voltage source). Among several subsystems, two are the most important: Reference signal generator and dc voltage controller. By receiving measurements/synchronization signals from the layers below, the former provides a current reference (e.g., 12 kHz could be a sampling frequency), whilst the latter is a PI controller for feedback regulating the dc bus (1.2 kHz the resulting sampling frequency of the previous example).

3) Converter Control Layer (Cnv): The feedback control is the main task of Cnv layer, which operates with a time constant of 10 μs – 1 ms. To this aim, the layer provides functions like phase locked loop, filtering of current/voltage measurements, voltage transformation, and converter current regulation by tracking the references generated in the App layer. The boundary between App/Cnv layers is defined by the control subsystems capable

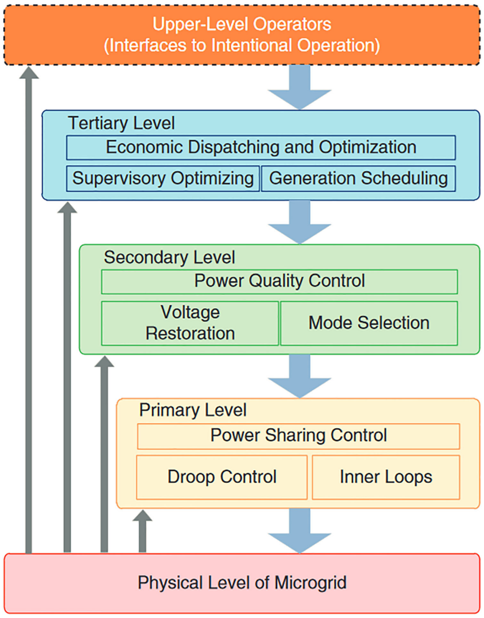

Fig. 4. DC microgrid hierarchical control architecture [14].

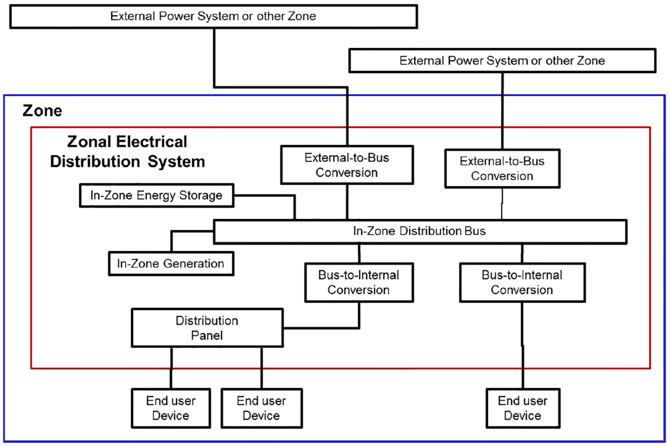

Fig. 5. Concepts of ZEDS and Zone [16].

of enabling the equivalent behavior (current/voltage source) of power converters.

4) Switching Control Layer (Swt): The Swt behaves as an interface between the control/hardware sections. Particularly, it provides the functions of modulation, switching logic, dead time generation, and diagnosis. The structure and the functionality of Swt layer are strictly related to the power converter topology. Regarding the time constant, a range from 1 to 10 μs is suggested by the IEEE Std 1662 and 1676 [10], [11].

5) Hardware Control Layer (Hwr): This layer is characterized by the lowest time constant, i.e., from 0.1 to 1 μs. Hwr layer is therefore responsible of directly supervising the power devices. To this aim, several are the functionalities to be applied, namely, gating, galvanic isolation, safe commutation, limits of di/dt–dv/dt, and first level protections.

C. Hierarchical Control of DC Microgrids

In the last years, the dc technology has been suggested also for microgrids [12], [13], leading to the proposal of a second hierarchical control architecture [14], [15]. In this regard, the Fig. 4 structure is advisable for the innate decoupling functionality between the control layers.

According to the authors, the control of ZEDS can be improved by taking into account the knowledge gained in dc microgrids branch. Particularly, the Fig. 4 structure has four different layers. Starting from the highest, the extended tertiary control is involved in achieving business benefits, which are paramount in land dc microgrids. The tertiary control layer guarantees the desired power flow between the external grid and the microgrid. The secondary level ensures the correspondence with PQ requirements, whilst the primary level is aimed at assuring the system stability and performing the power sharing (i.e., voltage droop functionality). Finally, at the physical level the main control loops (voltage/current) are responsible for managing each power converter of the dc microgrid.

D. IEEE Std 1826–2012

The standard 1826 [16] is concerned with the power electronics open system interfaces in zonal electrical distribution systems rated above 100 kW. Such a standard constitutes the natural transition of the previous concepts (IEEE Std 1676 and 1662) toward the ZEDS architecture. Additional remarks are part of a publication about standards in electrical ships [17]. The smallest logical–physical grouping of generation, storage, or consumption defines the so-called Zone. Three are the most important attributes which characterize a Zone: a) it contains one or more independent power device (i.e., converter, load, storage, generator), b) in normal operation, it works as an integral part of a larger system, and c) it is able to work independently for a limited period of time, under special operating conditions [16].

1) ZEDS at a Glance: As a part of a large power system, the ZEDS is aimed at supplying a group of loads. As shown in Fig. 5, a ZEDS (red box) and its loads represent a Zone (blue box), whereas one or more external power systems (or other Zones) are connected to the Zone thanks to a limited number of power/control interfaces. A well designed ZEDS is able to avoid the propagation of faults outside itself. At the same time, a ZEDS ensures specific PQ and quality of service (QoS) to the loads it supplies exclusively. The ZEDS is configured as a linking block among different power systems; thus, its main components are power converters, controls, and cables for delivering the desired power. Thus, energy storage and generation systems are considered as parts of a ZEDS only if the islanded operation is requested. By considering the Fig. 5 structure, this distribution proves to be convenient for shipboard power systems, as it enables redundancy, reconfigurability, fault resilience, and high efficiency. The ZEDS control is to be conceived to ensure three operating control states:

a) Centralized: By following a master–slave strategy, the central system controller (master) provides all the commands to the distributed subsystems (slaves);

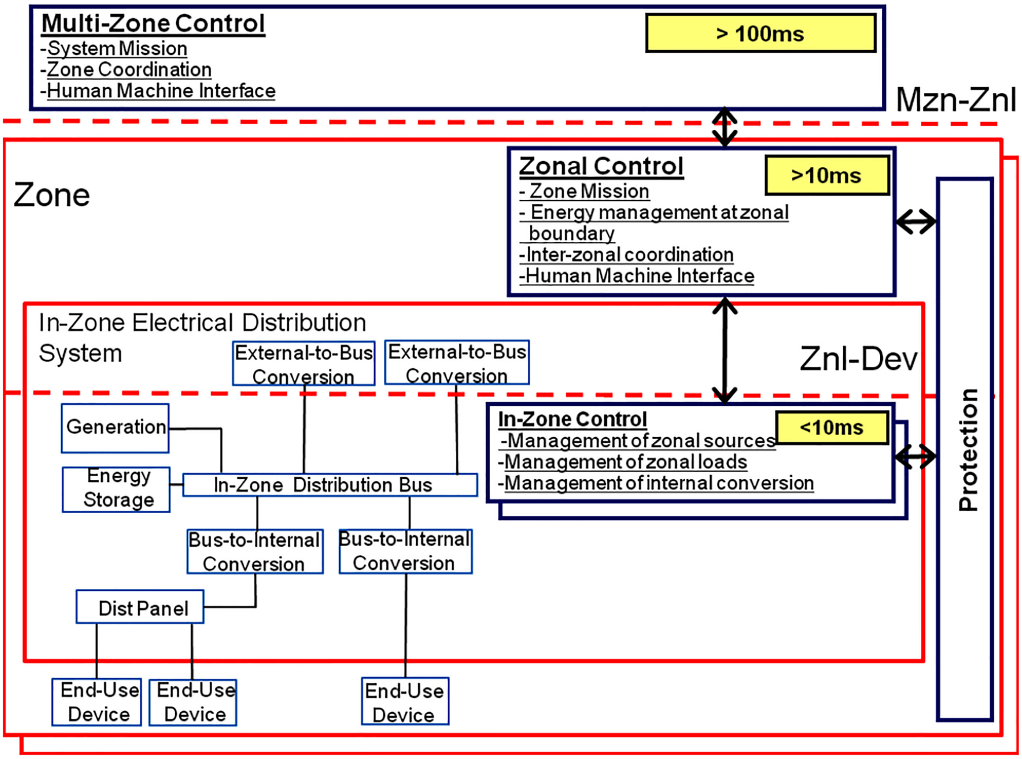

Fig. 6. ZEDS hierarchical control architecture [16].

b) Distributed: The control is made effective, by implementing independent/communicating controls and intelligent devices. The latter are strategically located to detect the conditions for initiating the required actions;

c) Autonomous: When independent controls make possible the global control functionality without communication with other devices. For better understanding the ZEDS capabilities, the system elements shown in Fig. 5 are described hereinafter.

2) Zonal Distribution System Elements: The first element to be cited is the external-to-bus conversion block, which manages the power flow (between external interface and in-zone distribution bus) and prevents fault propagation (from/to the external interface). A similar role is the one played by the in-zone distribution bus, which has to guarantee the proper power exchange among several subsystems (i.e., external-to-bus conversion, in-zone energy storage, in-zone generation, and bus-to-internal conversion). Then, high PQ/QoS requirements may be enforced by the in-zone energy storage system action. The electrical energy of a ZEDS can also be provided by an in-zone generation element, which basically transforms fuel chemical energy into mechanical then electrical. The bus-to-internal conversion element transforms the input electrical power into an output supply having the characteristics (type, PQ, QoS) demanded by end-use devices and/or distribution panels. Moreover, the conversion system protects the distribution panels from faults occurring into the panels themselves, to end-use devices, and to connected power cables. Finally, the distribution panel is an additional interface toward the final devices (i.e., similar to bus-to-internal conversion blocks), whereas the end-use device is usually an electrical load, but it can possibly be a source.

3) Power Interfaces and Control Power: The different elements previously described are to be connected through power electronics interfaces that must ensure electrical supply in accordance to IEEE Standard and IEC rules (for ac and dc systems). At the same time, they must assure no power interruption during the transition from one interface to another one. The embedded control system is managed by the so-called "control power," which is also involved in communicating with external networks and operating bus isolation (by means of devices/switches action). Once both the ZEDS structure and the actions of "power interfaces and control power" [16] have been determined, significant attention is to be paid to the control functional layers to enable the zonal distribution. In this regard, the three control functional layers depicted in Fig. 6 are explained in the following.

a) Multi-zone control: In the hierarchical ZEDS control structure, this layer covers the highest position. It directs the layer below (Zonal control) in order to coordinate the overall system mission and the duties of each zone/group. In some way, this layer corresponds to Sys layer of the PEBB structure (Fig. 3), whilst the advisable time constant should be above 100 ms.

b) Zonal control: Similarly to the previous layer, also this one has the task of managing the layer below (in-zone control), through a hierarchical control structure. The zonal control is responsible for imposing the zone mission while providing important functionalities: *i*) energy flow control at a zone boundary, *ii*) management of faults (i.e., detection, isolation, and reconfiguration), *iii*) interzonal coordination, *iv*) health/status of system

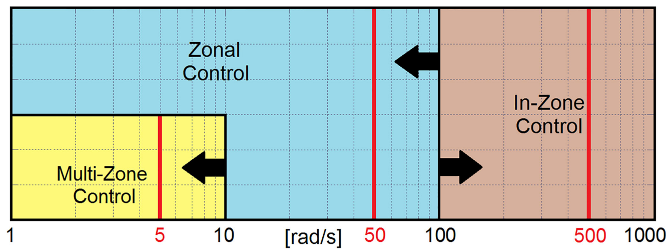

Fig. 7. ZEDS hierarchical control bandwidths.

control layer, *v*) human machine interface (HMI). For this control layer the time constant lower limit is ten times smaller than the previous one, so 10 ms.

c) In-zone control: The in-zone control is the key layer devoted to controlling the power electronics components. These ones are essentially involved in zonal sources-loads, and energy conversion. Moreover, power flow management, HMI, and fault detection are also accomplished in this layer, whose control time constant is smaller than 10 ms.

4) Interface Communication: Focusing on the interfaces between the three layers, an important consideration is related to the communication issue. Both zonal and in-zone control layers are indeed designed taking into account the need of a digital communication link to other supervisory control systems located in/out of the zone. This link is aimed at transmitting status information/commands from/to the upper/lower layer. For example, the power converters command is conveyed through this digital link.

5) ZEDS Control Bandwidths: The time constants [16] shown in Fig. 6 can be rearranged for establishing the control bandwidths at the basis of the hierarchical system coordination. For defining such control bandwidths, the first-order hypothesis can be done assuming that the controlled variables evolve by following a first-order behavior. Although this consideration could appear strong, actually it is a good starting point for performing a hierarchical control. By considering the first-order assumption thus mathematically inverting the time constants, the control bandwidths can be found in Fig. 7. As made evident by the graph, the position of bandwidths underlines a not complete decoupling between control loops. As is well known, this feature is usually appreciated in hierarchical control structure. For guaranteeing decoupling in ZEDS control, a convenient repositioning compliant with the standard could foresee a multi-Zone control bandwidth equal to 5 rad/s, whereas zonal and in-zone bandwidths should be, respectively, 50 and 500 rad/s. In Fig. 7, red lines highlight these suggested values, whilst black arrows represent the standard limits.

E. Models for ZEDS Analysis and Design

As a matter of fact, innovative ZEDS are to be designed basing on different models, whose studies can provide a first insight about these advanced controlled power systems. Taking into account the ZEDS complexity (e.g., control and coordination of several interacting power converters), the aforementioned models are therefore essential for correctly conceiving the ZEDS

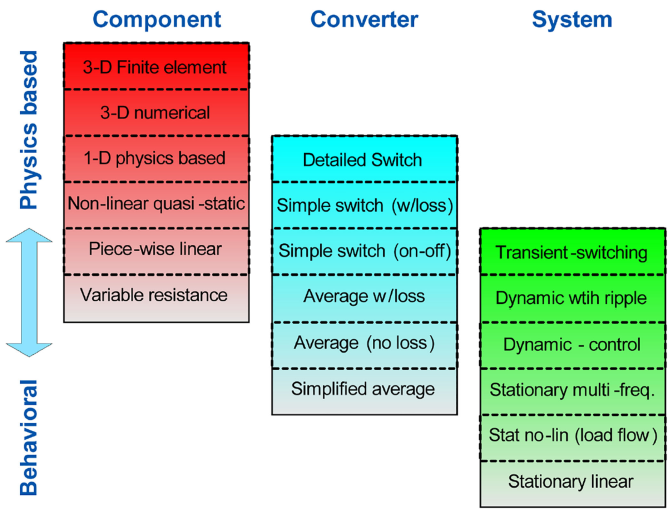

Fig. 8. Modeling classification [10].

functionalities, while at the same time prefiguring possible problems and criticalities. The importance of models is crucial, thus the IEEE Std 1662–2016 [10] has put the basis to define the modeling alternatives. As power converters enable the ZEDS operation, a particular attention is spent on this subsystem, whose modeling levels are classified as in Fig. 8.

1) Modeling classification: Once the classical intuitive grouping based on physical nature is overcome (i.e., electrical, thermal, etc.), a model's classification is aimed at separating the possible models into two main groups by observing the domain, behavioral or physical. A behavioral black-box model is only focused on its interactions with the external world, whilst the physical model precisely describes each internal element by laws based on physics. The two modeling approaches therefore take into account opposite views. In general, behavioral models are less accurate when used to represent extended operating ranges, while their accuracy increases in specific operating conditions. On the other side, physical model can provide more detailed results in a wide range, while their adoption is not always easy to be attained.

2) Modeling hierarchy: There are three hierarchies for modeling complex power systems, namely, component models, power converter models, and system-level models. As highlighted in Fig. 8, each level foresees different types of models, depending on requirements, classification, level of accuracy. By taking the power converter as an example, the modeling moves from the simplified average (behavioral classification) toward the detailed switch model, evidently a physical-based classification.

3) Degree of detail: As already expressed in Fig. 8, each component can be modeled with a different degree of detail. Then, the time scale of the phenomenon plays also a crucial role in modeling issues. By focusing on the main important component in ZEDS context, there are different ways for representing a power converter, depending on the modeling goals, namely, switching model, average model, linearized model, or

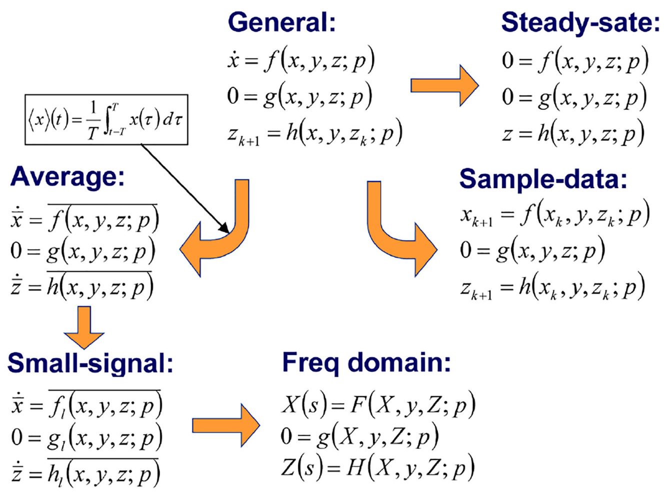

Fig. 9. Mathematical formulations [10].

steady-state power flow model. In particular, proper mathematical models (Fig. 9) can be build by defining the x variables (i.e. system dynamics), the y variables (i.e. algebraic constraints), the z discrete time parameters, and the system parameters p.

4) Reference domains: Models are usually defined in time domain, or in others domains where transformations can restore the time domain representation. If time domain models are generally adopted when simulating controlled power systems, the models in frequency domain (i.e., transfer functions or impedances) are useful in the stability analysis [1], harmonics, and EMI modeling and analysis.

5) Component model: For what concerns the models for representing the basic components, there are two main families: semiconductor switching device models and passive component models. In regarding to the first one, the available models move from the ideal switch (i.e., variable resistance from very large value-open switch to very small value-closed switch) to detailed complete physics-based models, where test data from manufacturers are essential. Similarly, for the passive component models (i.e., resistors, inductors, and capacitors), where detailed and simplified models are made available for the study of ZEDS. Another time, the models go from ordinary differential equations (i.e., lumped models) to Maxwell differential equations using finite elements (i.e., parasitic capacitances and inductances, cross-coupling effects, and so on and so forth).

6) Converter model: Based on the level of details, there are three main alternatives: switching models, average models, and discrete models. a) Switching models: in such a case, not only switching devices but also diodes are considered. These models are aimed at investigating the switching characteristics of the converters, thus studying the switching transients. They are used in circuit simulators, while ideal or simple switch models are enough in many system-level analyses. b) average models: When the converter time constant is sufficiently greater than the switching period, this kind of models can average the duty cycle over a switching cycle. As a consequence, the switching action is neglected in the continuous model whilst maintaining the slower nonlinear converter behavior. Once linearized the average model around the operating point, the linear system theory can be adopted to design the control, while assessing the small-signal stability. c) Discrete models: in such a case, the system is described in terms of a sequence of samples, one per switching cycle. Therefore, the converter action is modeled by a nonlinear and time-invariant difference equation. Also, in this case the linearization around an equilibrium point can offer the small-signal model (now evidently discrete), which exhibits a good accuracy at high frequencies (better than average models). Like continuous models, also discrete ones can be represented by simplified discrete models (i.e., sample data models), a combination between continuous average models and discrete models. Last models are used in digital control design of converters for pointing out nonlinear phenomena.

7) System model: As the power systems are generally given by a complex aggregation of subsystems, several modeling structures become necessary to study the possible phenomena. For giving a short list, it is possible to enumerate transient modeling, dynamic modeling, and steady-state modeling. a) Transient models: for analyzing the transient behavior, the switching model is adopted for the power converter; whereas lumped circuit elements are used for the other devices (sometimes parasitic components are also included). Regarding the control system, its action is neglected when the considered transient is sufficiently short. Otherwise, the controller can be partially (reduced order) or fully included in the analysis by taking into account the related time constants. b) Dynamic models: average models of power converters are conventionally implemented to study the system dynamic behavior. Also, the system stability can be verified by evaluating the models' behavior in frequency domain. A common approach to investigate the small-signal stability, foresees the linearization in a stable equilibrium point, as the starting models behave as nonlinear systems. As this analysis gives information about the stability in presence of small perturbations, the large perturbations are to be studied with nonlinear methods (e.g., Lyapunov). c) Steady-state models: usually this kind of model is based on power flow models (i.e., algebraic equations), albeit switching and average models are also the possible starting points. The steady-state models cover the harmonic studies. When the interaction between power converters and network can be neglected, the current source injection model is considered valuable. Conversely, other formulations (i.e. transfer function, Norton equivalent, harmonic-domain, or three-pulse models) have been proposed for overcoming this limitation.

III. Existing IEEE Standard and ZEDS Design Guidelines About DC Faults and Electrical Safety

The dangers related to faults in electrical systems can be classified in hazards for the system (e.g., equipment damage) and hazards for the people (i.e., electrical safety). The former are related to current or voltages exceeding the equipment maximum ratings, while the latter are caused either by the presence of harmful voltage on noncurrent-carrying metallic parts (e.g., touch voltage), or by arc related hazards (e.g., high temperatures, or ejection of hot fused materials and gases). Clearly, these two hazard classes are to be considered as intertwined, due to the extreme variability in both faults and system design. Moreover, the protective means used to cope with one class can affect the other, increasing the hazard management complexity. Consequently, the designer has to carefully evaluate the best compromise among the reduction of hazards for both the system and the people, the technical feasibility, the costs, and the applicable regulations.

To aid designers in managing faults and electrical safety hazards in dc ZEDSs, in this section the most relevant recommendations from Technical Standards are presented, highlighting the available degrees of freedom in design and the actual critical points. Moreover, the technologies available at present for protecting dc ZEDS, as well as their pros and cons, are depicted, to provide a complete overview on this topic. For the sake of simplicity, in the following the rail-to-rail faults and electrical arcing are discussed in the dc faults protection section due to their common features (high current, little effect on grounding potential). Conversely, ground faults are discussed in the electrical safety section due to their relation with touch voltage.

A. Designing DC ZEDS, the Issue of DC Faults Protection and Electrical Safety

In general, protection in dc power systems is more complex than in ac, due to the following peculiarities: 1) lack of current zero crossing; 2) presence of energy storing components; 3) fast and severe current transients; and 4) fault behavior dependence on converter topology and system grounding. Some of these challenging aspects are strictly related to the actual dc power system paradigm, which exploits power electronics. The converters operation depends on their control systems, which affect fault behavior in both positive and negative ways. For example, a converter supplying a rail-to-rail fault limits the fault current to a value near to the rated current, thus avoiding damages, while at the same time impairing the fault localization.

The presence of energy storing components in a dc system, like inductors and capacitors, is needed to build filtering stages, thus allowing complying with the PQ requirements. At the same time, filters deeply affect fault transients. In fact, the first fault current transient is caused by capacitors discharge, which has low longitudinal impedance and thus lead to high magnitude current with very short rise times. Conversely, inductors can worsen arc faults issues, making the fault current interruption more difficult.

Both grounding and converter topology affect fault current path, complicating its determination. Moreover, the latter issue is worsened by the significant number of configurations a ZEDS can have. Finally, galvanic isolation in interface converters (between different zones and between them and ac supply) and filters with ground connections can increase complexity too. Arc faults are recognized as a critical issue for high voltage dc systems. At present, there is a lack of universally recognized practice to assess their effects. However, with the related hazards being similar to the ones present in the ac systems, it can be supposed that the protection approach can follow the same base concepts (e.g., arc detectors and reinforced switchboards). Concerning touch voltage, the grounding of both ac and dc supplies and loads is relevant, as well as converter topologies and the presence of galvanic isolation. However, in marine systems the natural bonding and grounding provided by the hull can be beneficial in this regard, due to the additional bonding path that is always at ground reference voltage. Conversely, issues can arise at interfaces among hull and external masses in specific conditions, like at hull/water interface during ground faults in shore connection operation [18]. To correctly design a ZEDS protection system, all of the abovementioned critical points need to be assessed by the designer, incorporated in the system design analysis, and managed properly.

B. Recommendations From Standards Regarding DC Faults and Electrical Safety

At present, a comprehensive short-circuit fault management framework within dc ZEDS is lacking. Though, the IEEE Std 1709 [1], 1826 [16], and 1662 [10] are relevant to the topic, while some indications regarding faults and electrical safety can be also found in: IEEE Std 1628 (“IEEE Recommended Practice for Maintenance of DC Overhead Contact Systems for Transit Systems”); IEEE Std 1100 (“IEEE Recommended Practice for Powering and Grounding Electronic Equipment”); and IEEE Std 142 (“IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems”). In the following, a summary of the recommendations from the three main IEEE Standards concerning dc faults and electrical safety are given.

In general, the Standards 1709 and 1826 are aimed at defining recommendations at system level, while 1662 is focused on component level. Moreover, 1826 is more conceptual, while 1709 and 1662 are more practical oriented. For what concerns grounding, 1709 recommends high resistance grounding (HRG) or solid grounded middle point. In 1662, HRG is defined as a necessity when the voltage rises (above 1 kV), but in general the grounding selection is left to the designer. Indeed, 1662 states that power electronics (PE) to be installed in existing facilities have upstream grounding already defined, but PE input grounding could be managed at will if an input transformer is used. Conversely, downstream grounding is a free choice, if the downstream equipment works correctly. In 1662–Annex B “Power Electronics in marine power systems,” the HRG with two resistors is recommended for marine dc applications. Existing practices for dc grounding are also depicted in IEEE Std 45, 142, 1100, and in IEC 60092.

Regarding bonding, Std 1662 recommends a solidly grounded one to provide a low impedance return path in case of ground faults, thus lowering touch voltages. This is not specifically recalled in Std 1709, where it is only mentioned to take into account and comply with existing touch voltage limits. However, when discussing the first grounding option in Std 1709, a mention about metal bodies grounding is made. In fact, in ungrounded systems the connection of all metal bodies to the ground is recommended for safety purposes. The use of galvanic isolation is recommended by both 1709 and 1662, either by means of ac side transformers or by means of isolated converters. The Std 1826 specifically refers to Std 1662 in this regard.

The general protective functions are specified in Std 1826 for interface converters, and some of these are recalled in 1709 and 1662 standards: current limitation; time-limited current withstanding capability; catastrophic failure due to overcurrent events prevention; maintenance lockout or bypass; load break capability at input–output; self-monitoring and protection; and internal energy discharge. In addition, Std 1826 specifies that interfaces must prevent fault propagation from downstream to upstream and vice versa. Regarding these functions, a single component can provide one or more of them, protective ones included, depending on the control algorithm application. This concept is recalled also in Std 1709, which highlights the independency among interruption, isolation, and configuration functions. Equipment dedicated solely to protection function [e.g., circuit breakers (CBs)] is also considered by standards. However, as 1709 recommends, all the converters should participate in fault clearing with proper coordination with the other elements. Thanks to this capability, most load-side circuit breakers may be replaced by simple switches, such as dc disconnect switches. Similarly, each subsystem devoted to a specific function (energy storage, propulsion, etc.) that can be attached to the main dc buses needs to be able to connect, disconnect, and isolate itself from the system through its own means. Regarding the generators, they still need a protection device between then and the converters, as a protection from converter's internal faults. This can be easily achieved for rotating machines by means of standard protection devices installed on the ac generator's output, while other power generating devices that have a direct dc output (e.g., fuel cells) will need dedicated dc breakers. It is worth noticing that generators should also be protected from reverse power flows, if bidirectional rectifiers are used.

In Std 1826 a set of control functions for interface converters are defined, which impacts also on faults and electrical safety: monitoring; information exchange; control; and protection. Both the zonal and in-zone control layers are relevant: The former must provide coordination for fault-detection, isolation, and reconfiguration, while the latter must provide autonomous fault detection, isolation, and reconfiguration in coordination with the zonal controller. In this regard, 1662 specify some additional functions that have to be integrated in the PE (interfaces included): overcurrent protection, short-circuit protection, fault protection and stored energy, and reverse current protection. Particular requirements are the ones regarding short circuit, which imply the capability of managing the fault current for system protection and provide fault-current-limiting feature. The PE should also protect surrounding environment and personnel by automatically shutting down before the current reaches a fatal level, deenergizing its output and isolating itself from the system. All the stored energy has to be dissipated upon deenergization.

Regarding specific protective equipment, the Std 1709 recommends avoiding fuses for protecting the main MVdc buses, while they can still be used for other purposes, like backup protection or PE internal fault protection. The latter function is specifically recalled in Std 1662. In addition to this, Std 1709 recommends using differential-type protections in place of overcurrent ones, to overcome the issue given by the inherent current limitation performed by the PE. The latter Standard also recommends that all power sources should actively limit fault currents, to ease the connection of different size generators, storage devices, and loads.

Some general requirements (present also in conventional ac systems) still apply in dc. These are recalled throughout all the standards: isolation upon disconnection; safety locks and interlocks for personnel safety during maintenance; protection from direct contact with conductive parts; and arc-fault protection (by means of proper grounding, enclosures, and other means such as arc sensors).

Regarding insulating systems, Std 1709 specifies some requirements for avoiding premature failures, e.g., taking into account the presence of high-frequency current components and voltage deviation during faults. The IEEE Std 1580–2001 for dc cables and insulated bus pipes still apply.

Both Std 1709 and 1662 specify the recommended studies and analyses to be performed in order to both assure the compliancy with the requirements and demonstrate the design correctness. In particular, both standards state that modeling and simulation play a key role in the design and testing processes, due to the peculiarities of modern dc systems.

Finally, in both 1709 and 1662 specific recommendations regarding design for safety are present. The aim is to overcome the actual absence of international guidelines for safety in dc systems above 3 kV and the presence of several different local rules for the lower voltages. Reference is made to IEEE Std 1628 and to MIL-HDBK-1025/10. Uncovered issues, like touch voltages during faults, are to be properly considered during system design and equipment layout.

C. Practical Issues for Protection

The presence of a number of factors affecting fault behavior makes the fault management of dc ZEDS a complex issue. There are several methods, techniques, and components that can be used for defining it (e.g., refer to [19]–[23]), but these are outside the scope of this article. However, some general issues and requirements need to be considered.

1) Current Sensor Requirements: To provide the protection function, information from current sensors is needed. The sensors can be integrated either into converters or breakers, or be standalone components. Given the dc fault peculiarities, the most significant requirement is the capability to accurately measure fast transients of high magnitude currents. Several current sensors can be used, such as current transformers, Hall effect sensors, shunt resistances, and Rogowski coils. Their pros and cons are shown in Table I [19]. Among the considered sensors, the Rogowski coil seems to be the most suitable one. However, it requires an integrator to provide the current value starting from the voltage induced on the coil, which in turn needs to be designed for the specific application. Moreover, Rogowski coils cannot measure steady state dc currents.

In this regard, it may be useful to install in the system different type of sensors, aimed at separately providing data in normal and fault conditions. This is naturally achieved when implementing protection through solid state CBs. Indeed, CBs have their dedicated current sensors for fault detection, while converters have their integrated ones for normal operation.

2) Data acquisition and Management, and Computational Power Requirements: As abovementioned, the first transient in

TABLE I
COMPARISON OF DIFFERENT CURRENT SENSORS

	Transformer	Shunt	Hall Effect	Rogowski coil
Cost	Medium	Very low	High	Low
Linearity	Fair	Very good	Poor	Very good
High current measurement capability	Good	Very poor	Good	Very good
Power consumption	Low	High	Medium	Low
Current saturation issue	Yes	No	Yes	No
Output variation with temperature	Low	Mediu m	High	Very low
DC offset issue	No	Yes	Yes	No
Saturation & Hysteresis issues	Yes	No	Yes	No

dc fault currents is fast and has a high magnitude, caused by the filters' capacitors discharge. After the first current pulse, a steady-state fault current supplied by the power sources flows through the interface converters. To limit the damage to the system components, the best approach is to intervene before the first transient reaches its maximum. Thus, fault detection and isolation actions must be completed in a very short time (e.g., in less than a couple of milliseconds). This time is at least one order of magnitude lower in respect to what is actually achieved in ac systems. While the simple current interruption can be achieved in such a short timeframe (e.g., solid-state CBs can intervene in microseconds), in the same time it is also required to perform other tasks. For example, measurements/calculations needed to detect, locate, and isolate the fault, as well as storing the data for the postfault reconfiguration activity. Thus, a fault management system requires significant data acquisition, storing, and communication resources, plus adequate computational power.

3) Selectivity and Coordination Challenges: The isolation of the faulted element is accomplished through the intervention of a proper set of breakers and/or disconnectors, acting at the boundary of the section to be isolated. The goal is to detach the smallest power system section containing the faulted element. The definition of the boundary can be achieved by means of different techniques, exploiting a concentrated approach, a distributed one, or a mixed one. Regarding the distributed approach, it clearly needs proper selectivity and coordination among protective relays. In ac systems, this approach is applied by means of the definition of current/time triggers for each device, possibly aided by directional relays interlock. However, in dc ZEDS selectivity and coordination are more challenging. In fact, the fast current transient makes selectivity through time delays nearly unfeasible (the tens to hundreds of milliseconds delays used in ac are clearly too much for dc applications), while the system's low impedance makes it difficult to define selectivity through current thresholds only. A possible solution is the use of differential or zone-based directional relays, coupled with fast logical signal exchange with neighbor breakers to create suitable interlocks [21]. Conversely, the no-load disconnectors rely on trigger signals coming from the related converters, which can already exploit directional current sensing capability in their normal operation. Concerning the concentrated approach, it is based on a main control system that defines the proper set of devices to be opened in order to isolate the fault, based on the data provided by the several sensors installed in the power system. The presence of a single control system allows to easily define the optimal isolation boundary, as well as to properly coordinate the breakers/disconnectors opening. Moreover, in case of a fault in a breaker/disconnector, the concentrated approach is able to define a new optimal isolation boundary, while the distributed one can lead to a wider power outage. Due to the need of data exchange and boundary calculation, the concentrated approach presents also the abovementioned class of challenges ("data acquisition and management, and computational power requirements"). Moreover, a fault in the concentrated control system or in data acquisition and exchange systems is critical, thus leading to the need of a simpler fallback system. The latter can be achieved through a simplified distributed system, thus favoring system safety in place of an accurate selectivity.

4) Standardization and Interoperability: In ac systems there are several standards and requirements regarding the components that can be integrated into a power system. These allow the producers to design, build, and sell equipment that is guaranteed to correctly operate when installed in a power system designed following the standards. At present, the regulatory framework for the dc systems is still in its infancy, thus causing serious gaps in interoperability among different equipment (fault management included). In this regard, several groups are currently working toward defining new standards, codes, and regulations regarding dc systems, eventually leading to the improvement of standardization and interoperability in this technical area. This will not only ease the work of the designers but also cut costs in equipment supplying.

D. Electrical Safety in DC Systems:

The electrical safety is achieved through a set of organizational measures and technical means, aimed at preventing hazards for people related with the use of electricity. Excluding the dangers due to electrical arcing, the most significant electrical safety issues are caused by direct and indirect contacts. The former concerns the contact of people with current carrying parts, while the latter regards the presence of harmful voltages on noncurrent carrying metallic parts (commonly due to a ground fault).

The protection from direct contacts does not present particular issues in dc, as it is possible to apply the well-known insulation and physical separation concepts. However, there are open challenges for dc insulating systems life, related to the electrical and thermal ageing caused by currents with high-frequency content [24].

For what concerns indirect contacts, these are commonly managed through grounding and protection coordination. In this regard, a safety curve for dc systems is already present in actual standards and regulations, while the fault clearing time depicted in Fig. 2 is only an indication of the maximum allowable times for clearing a fault, related to the fault ride through capabilities of the converters. Thus, it has not to be used for electrical safety assessment. It is worth noticing that an issue can arise in relation to the place in which the ground fault happens. In fact, the time/current and time/voltage safety curves are defined in systems with undisturbed dc voltages, while modern systems have power electronics working with high-frequency commutation. While the dc voltage on buses can be considered as an undisturbed one thanks to the filters' presence, the converters output present a highly varying waveform. If such a distorted voltage is applied to a person (due to a ground fault), the compliancy with dc voltage/time (or current/time) safety curves may be insufficient to guarantee its safety. As it is impossible to define new safety curves for each combination of voltage, switching frequency, and waveform, the best solution lies in reducing the extension of the critical sections (i.e., installing the filters as close as possible to the converters). The possibility of having a fault that originates in these sections is therefore reduced, thus removing this issue.

Regarding the system grounding, both the Std 1709 and 1662 recommend the HRG for marine systems. In particular, the latter recommends the two-resistor grounding arrangement, due to the possible installation of converters lacking an accessible central neutral point. This is reasonable because it allows attaining the advantages of ungrounded systems (frequently used in marine sector in LV systems), while at the same time avoiding the voltage deviation during normal operation. However, during ground faults the nonfaulted rail reaches the full dc voltage, thus requiring a proper insulating system design. Moreover, the resistors introduce additional losses, due to the current they drain from the buses toward the ground. These losses can be limited by using high resistance values (in the MΩ order of magnitude [25]). A proper design of their cooling system is still needed, to avoid premature ageing and related faults. An additional advantage in the two-resistor HRG in terms of electrical safety is the simple detection of ground faults. Indeed, it is possible to sense the variations in the currents flowing through the resistors by means of current sensors with differential relays. This is simpler than the insulation measurement systems needed in ac ungrounded systems. Converters can also be used to provide ground-fault detection, either through already present sensors or by means of additional ones.

The Std 1662 recommends using galvanic isolation in the PE that works as an interface among zones, which is also beneficial for electric safety. Indeed, galvanic isolation allows considering each subsection as a separate system, with related benefits in its design. This is also recalled by Std 1709, which states that loads requiring an independent ground are to be connected to the MVdc bus by means of converters endowed with a high-frequency transformer, to provide galvanic isolation. Conversely, if nonisolated converters are used, the ground-fault behavior depends on both sides grounding, thus leading to several possible cases. An example of such an eventuality is given in [26]. However, if the system has a significant power level, thus requiring HV generators ($>$1 kV in marine sector), the connection of their neutral point to ground with a properly sized high value resistance is required. This has the additional benefit of making it possible to detect ground-faults in the nonisolated downstream section by means of a single current sensor on the generator grounding resistor. Thus, it is possible to cut costs at the price of lowering the localization accuracy (it is not possible to detect which of the two dc rails is faulted).

In contrast to what happens with rail-to-rail faults, the action following a ground fault (i.e., deenergization or continued operation) affects also electrical safety. If the resulting touch voltages are below the safety curve limits, the system can continue to operate and the fault can be repaired at the most suitable time. Otherwise, the faulted section needs to be deenergized in accordance with the safety curve time limits. The grounding of generators, distribution system, and loads affects also the system's common mode behavior, which may be an issue if not properly managed. It is worth noting that dc current flow in the ground during normal operation is not allowed.

E. Final Comments About Protection and Electrical Safety

Considering all the information depicted above, it is clear that at present a coherent framework for designing dc ZEDS protection is lacking. However, useful recommendations can be found in different technical standards for DC systems, while several topics are already discussed in standards regarding AC systems. As a summary, taking into account all the standards analyzed above, the following points constitute the actual recommended practice:

1) HGR with two resistors, one for each rail. (Like in actual HV marine dc systems.)
2) Use of galvanic isolated power electronics converters as much as possible. (To avoid fault current paths flowing through different zones, thus easing the protection and grounding definition, and improving electrical safety.)
3) Solidly grounded bonding for all the noncurrent carrying metallic parts. (Naturally achieved in marine systems thanks to the hull mounting equipment.)
4) Design through modeling and simulation tools for protections and electrical safety, allowing developing information not available at present.
5) Demonstration of the design correctness to stakeholders through modeling, simulation, and tests.

A couple of other comments can be given. First, all the standards are in accordance for what concerns the required protective functions, but their specific implementation is up to the designer. Second, fuses are not recommended for system protection, but they can be used for protecting components or feeders. Consequently, protective functions have to be integrated into converters, or provided by dedicated devices. Third, Std

1709 recommendation about using differential-type protections in place of overcurrent ones may or may not be applicable depending on the specific ZEDS operation concept. In fact, radial operated ZEDS using the zonal architecture to only provide reconfiguration options can successfully use overcurrent protection. Anyhow, the latter are to be integrated in all the ZEDS, in order to protect the PE, manage faults in downstream radial sections, and as a fallback system. Finally, although Standards lack specific recommendations for some topics, they suggest general practices that are similar to the ones given for ac systems, electrical safety ones included.

Overall, the issue of correctly designing dc ZEDS actually has not a single solution, due to the system complexity and the wide range of different possible cases that can arise in a real system. To this aim, the standards recommend to apply a design approach based on analysis, simulation and modeling, considering a set of possible faults and combinations. As an example, Std 1709 depicts a series of possible location for the faults. Then, it recommends performing the studies with a variety of fault impedances, to assess the system behavior in presence of all the possible spectrum of faults that can happen in a real system. The Standard also highlights the need of study postfault reconfiguration, thus recalling what has been also mentioned in the "practical issues for protection" section. The need of designing the system with the power rerouting function embedded, and to provide safe procedures for replacing the components for post-fault power restoration (by using hot-swappable modules where necessary to comply with high QoS requirements) is also highlighted. It is remarked that time domain computer system analyses have to be applied for all the faults studies, since they are the only ones able to fully capture the transient in dc systems, by using proper modeling assumptions to assure their correct representation. All the recommended studies have the goal of demonstrating the effectiveness of the designed fault management system, to overcome the present absence of a recognized practice.

To address this issue, at present several regulatory bodies and classification societies have tackled the issue of defining rules and regulation for the correct design of dc systems onboard ships. Thus, in the next years a clearer vision on these topics is foreseen, also thanks to the amount of research work that both academia and industry are producing into this topic.

IV. ICT Related Requirements

In the previous sections it has been mentioned several times that both the voltage/power control and the fault protection framework in ZEDS require a fast and reliable communication infrastructure. In this regard, Std 1826 provides some indications that can be generally applied to both the topics analyzed in the two previous specific sections, with a specific focus on the interface requirements.

The first requirement is related to the boundaries between control functional layers (refer to Fig. 3). These must contain all the ICT interfaces needed to exchange control, monitoring, and protection information between the layers. A specific mention is given to IEC 61850, as the baseline set of requirements that shall be followed unless otherwise specified. Such requirement is applicable to all the power electronics converters integrated in a dc ZEDS, since it concerns the single converter control architecture.

Concerning the overall zonal architecture, the Std 1826 provides requirements for digital communication links depending on the specific hierarchical level (refer to Fig. 6). In general, digital communication links have to be provided among all the levels, to allow transmitting and receiving control, monitoring, and status information. Regarding each single hierarchical level, a minimum set of data items to be exchanged among them is defined. The digital communication link between multizone system layer and zonal layer controllers have to exchange, across their digital communication links, at a minimum the following: Data to define the mission of a zone; status information for coordination of zones; receive health/status from and provide control commands to zonal level control; data used by an HMI that provides a means for the operator to handle each type of alert and to review alert status for the zones as a whole. For what it concerns the zonal layer control system, it is required to install a digital communication link to other supervisory control systems located in or out of the zone, dedicated to transmitting status information and receiving commands from the above layer. A zonal control interface is also to be provided, by means of a control panel interface or HMI. The Std 1826 depicts the minimum data items to be displayed to the operator, and the minimum set of commands that have to be provided through this control interface. The latter are, transition between control modes, transition between local and remote modes of control, manual control of isolating switches, adjustment of control, and regulation set points.

V. Conclusion

The article provides a comprehensive review of applicable IEEE Standards about the topics of control system architectures and fault protection capabilities of ZEDS in marine systems. In respect to [27], here the models for ZEDS analysis and design, as well as some basic requirements regarding ICT, have been included.

As it is clear from the above discussion, at present the design of dc ZEDS is not a straightforward task. The standards provide useful insights, but there are several gray areas and topics whose analysis is not sufficiently deepened to give specific indications to a designer. This is well represented by the following basic design principle, stated in the IEEE Std 1709: "The MVdc power system must generate, store, and deliver electrical power of the proper quality and continuity to the served loads with minimal risks." The standard sets a goal, as well as providing several suggestions and recommended practices, like the use of automatic bus transfer switches to enhance the continuity of power. However, different solutions can still be suitable, provided that they allow attaining the abovementioned goal. This issue will gradually disappear as time goes on, given the work currently done by both researchers and regulatory bodies in this regard.

However, another issue for the industry remains open, which is the dc ZEDS qualification. In fact, it is needed to confirm the adequacy of the equipment to perform its function (or functions) over the expected range of operational conditions, which could include any combination of normal, abnormal, events, or in-service test conditions. This is obviously an issue, given the lack of prior knowledge and experience about the operation of such innovative systems. Definition of qualification is different in every industry and generally, it is considered a subset of validation efforts such as described in Clause 7 of IEEE Std 1826–2012 [16], the IEC/IEEE International Standard 60780-323-2016 - Nuclear facilities – Electrical equipment important to safety – Qualification [28], and IEEEE Std 627 Standard for Qualification of Equipment Used in Nuclear Facilities [29]. The last two standards were originally based on US Navy nuclear reactors standards and were deactivated after 1970 and then reactivated after Fukushima Daiichi nuclear disaster.

"You have to learn from the mistakes of others. You won't live long enough to make them all yourself" by Admiral Hyman G. Rickover.

References

[1] *IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships*, IEEE Standard 1709–2018 (Revision of IEEE Std 1709-2010), Dec. 7, 2018.

[2] M. Belkhayat, R. Cooley, and A. Witulski, "Large signal stability criteria for distributed systems with constant power loads," in *Proc. PESC ' Power Electron. Specialist Conf.*, Atlanta, GA, USA, 1995, vol. 2, pp. 1333–1338.

[3] A. Kwasinski and C. N. Onwuchekwa, "Dynamic behavior and stabilization of DC microgrids with instantaneous constant-power loads," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 822–834, Mar. 2011.

[4] D. Bosich, G. Giadrossi, and G. Sulligoi, "Voltage control solutions to face the CPL instability in MVDC shipboard power systems," in *Proc. AEIT Annu. Conf. - From Res. Industry: Need More Effective Technol. Transfer*, Sep. 18–19, 2014, pp. 1–6.

[5] A. Vicenzutti, D. Bosich, and G. Sulligoi, "MVDC power system voltage control through feedback linearization technique: Application to different shipboard power conversion architectures," in *Proc. IEEE Electric Ship Technologies Symp.*, Arlington, VA, USA, 2013, pp. 303–307.

[6] G. Sulligoi, D. Bosich, G. Giadrossi, L. Zhu, M. Cupelli, and A. Monti, "Multiconverter medium voltage DC power systems on ships: Constant-power loads instability solution using linearization via state feedback control," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2543–2552, Sep. 2014.

[7] T. Ericsen, N. Hingorani, and Y. Khersonsky, "PEBB - power electronics building blocks from concept to reality," in *Proc. Record Conf. Papers - IEEE Ind. Appl. Soc. 53rd Ann. Petro. Chem. Ind. Conf.*, Sep. 11–15, 2006, pp. 1–7.

[8] N. Hingorani, H. Ginn, and J. Sullivan, "Control/protection architecture for power electronic converters," in *Proc. IEEE Electric Ship Technologies Symp.*, 2011, pp. 472–477.

[9] H. L. Ginn, N. Hingorani, J. R. Sullivan, and R. Wachal, "Control architecture for high power electronics converters," *Proc. IEEE*, vol. 103, no. 12, pp. 2312–2319, Dec. 2015.

[10] *IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems, IEEE Standard 1662-2016 (Revision of IEEE Standard 1662-2008),* Mar. 9, 2017.

[11] *IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems, IEEE Std 1676-2010,* Feb. 11, 2011.

[12] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—part I: A review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, Jul. 2016.

[13] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "DC microgrids—Part II: A review of power architectures, applications, and standardization issues," *IEEE Trans. Power Electron.*, vol. 31, no. 5, pp. 3528–3549, May 2016.

[14] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J. C. Vasquez, and J. M. Guerrero, "Next-generation shipboard DC power system: Introduction smart grid and dc microgrid technologies into maritime electrical netowrks," *IEEE Electrific. Mag.*, vol. 4, no. 2, pp. 45–57, Jun. 2016.

[15] Z. Jin, L. Meng, J. C. Vasquez, and J. M. Guerrero, "Specialized hierarchical control strategy for DC distribution based shipboard microgrids: A combination of emerging DC shipboard power systems and microgrid technologies," in *Proc. IECON 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, 2017, pp. 6820–6825.

[16] *IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW*, in IEEE Standard 1826-2012, Jun. 22, 2012.

[17] Y. Khersonsky and G. Sulligoi, "Standards for ships and oil platforms: A review of the latest from the IEEE and IEC," *IEEE Industry Appl. Mag.*, vol. 22, no. 1, pp. 20–27, Jan./Feb. 2016.

[18] G. Sulligoi, D. Bosich, R. Pelaschiar, G. Lipardi, and F. Tosato, "Shore-to-ship power," *Proc. IEEE*, vol. 103, no. 12, pp. 2381–2400, Dec. 2015.

[19] K. Satpathi, A. Ukil, and J. Pou, "Short-circuit fault management in DC electric ship propulsion system: Protection requirements, review of existing technologies and future research trends," *IEEE Trans. Transp. Electrific.*, vol. 4, no. 1, pp. 272–291, Mar. 2018.

[20] E. Haugan, H. Rygg, A. Skjellnes, and L. Barstad, "Discrimination in offshore and marine dc distribution systems," in *Proc. IEEE 17th Workshop Control Model. Power Electron.*, Jun. 27–30, 2016, pp. 1–7.

[21] H. Bardideh, A. Fidigatti, and E. Ragaini, "Redundant directional zone selectivity for marine electrical installations," in *Proc. AEIT Int. Annu. Conf.*, Oct. 3–5, 2018, pp. 1–6.

[22] R. M. Cuzner and V. Singh, "Future shipboard MVdc system protection requirements and solid-state protective device topological tradeoffs," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 1, pp. 244–259, Mar. 2017.

[23] R. M. Cuzner, V. Singh, M. Rashidi, and A. Nasiri, "Converter topological and solid state protective device trade-offs for future shipboard MVDC systems," in *Proc. IEEE Electric Ship Technologies Symp.*, 2015, pp. 34–39.

[24] L. Bao, J. Li, J. Zhang, X. Li, and X. Li, "Influences of temperature on partial discharge behavior in oil-paper bounded gas cavity under pulsating DC voltage," *IEEE Trans. Dielectrics Elect. Insul.*, vol. 23, no. 3, pp. 1482–1490, Jun. 2016.

[25] Y. Wang, Z. Yu, J. He, S. Chen, R. Zeng, and B. Zhang, "Performance of shipboard medium-voltage DC system of various grounding modes under monopole ground fault," *IEEE Trans. Industry Appl.*, vol. 51, no. 6, pp. 5002–5009, Nov./Dec. 2015.

[26] A. Vicenzutti, F. Tosato, E. De Din, and G. Sulligoi, "Studies on asymmetrical short circuit currents in shipboard medium voltage direct current distribution systems fed by AC generators," in *Proc. IEEE Electric Ship Technologies Symp.*, Alexandria, VA, USA, 2015, pp. 48–53.

[27] G. Sulligoi, D. Bosich, A. Vicenzutti, and Y. Khersonsky, "Design of zonal electrical distribution systems for ships & oil platforms: Control systems and protections," in *Proc. IEEE Petroleum Chem. Industry Committee Conf.*, Vancouver, BC, Canada, 2019, pp. 321–330.

[28] *IEC/IEEE International Standard - Nuclear facilities – Electrical equipment important to safety–Qualification, IEC/IEEE Standard 60780-323,* Feb. 19, 2016.

[29] *IEEE Standard for Qualification of Equipment Used in Nuclear Facilities*, IEEE Standard 627-2010 (Revision of IEEE Standard 627-1980), Jun. 4, 2010.

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