WHITE PAPER

Hierarchical power and energy control for advanced power systems

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Modern ship power systems are highly integrated solutions combining a multitude of sources and consumers. The power system is an enabling platform for the use of alternative fuel sources as well as energy storage and is thus an essential component in the implementation of low-carbon maritime transportation. Batteries, fuel cells as well as bidirectional hybrid drivelines are all novel sources and consumers which are now enabled by electrification.

By virtue of their isolated nature, ship power systems are self-sustaining microgrids, and have traditionally consisted of AC power systems supplied by a number of diesel generator sets. This microgrid has strict requirements of robustness and reliability due to the very nature of it being the sole source of power for essential consumers as well as propulsion and manoeuvring systems. Control of such AC microgrids is the responsibility of the Power Management System (PMS), a higher-level controller whose overall goal is ensuring the availability of power and avoiding a blackout. With multiple generators, the PMS can prioritise operation and balance the available power reserve with the actual consumed power. This optimization is therefore concerned with instantaneous power.

This situation becomes more complex with the introduction of energy storage, sources with alternate fuels and a push for efficient energy usage. This additional dimension of time and energy is not a factor available in the functionality of classical power management. Rather than adding complexity to the same existing control system, a more elegant approach is to separate functions in a hierarchical structure. This allows a clean compartmentalization of control system scope, while facilitating reuse of mature products and conversely the focusing of specialized algorithms for specific control systems in specific layers. Decisions related to Energy (power with the added consideration of time) become the scope of a higher level control system termed the Energy Management System (EMS).

Complex power and propulsion systems allow an increased number of operational configurations and supply possibilities. In each unique operational mode or step, an optimal configuration and a set of power setpoints (load sharing) can be determined. For each load demand, this optimum can be different, based on the performance objectives, such as low emissions, low maintenance or high performance. For example, the power setpoints in free sailing can be optimized for low fuel consumption and low running hours, while addressing availability during manoeuvring. Typically however there is a combination of performance objectives, such that a compromise always needs to be addressed.

Determining the optimal setpoints for the energy system needs to consider information from many other systems and sources, conceptually illustrated in Figure 1. Here an optimization algorithm is represented, which aims to find optimal configurations across multiple variables, taking into account external constraints and system inputs. The expected load demand can be based on environmental conditions, route information, mission of the ship, etc., but also the condition of onboard energy storage or energy sources.

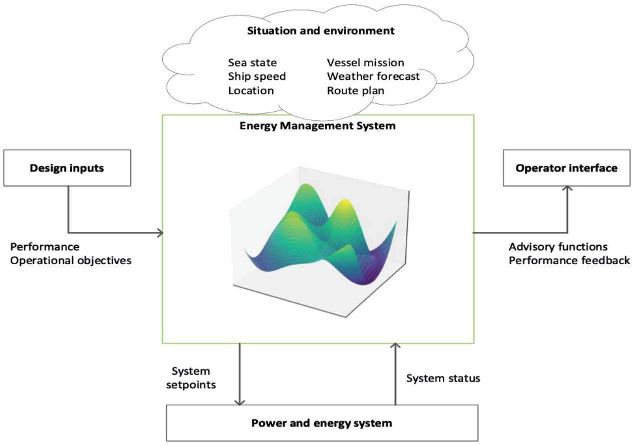

Figure 1. Conceptual illustration of information flows for an EMS.

This optimization and collation of information from multiple sources is not within the capabilities of a typical PMS, which has the objective to ensure and control the power availability in an electrical system. The PMS is basically only controlling the electrical system's supply and has a very limited interaction with the other ship's systems. An EMS, on the other hand, has the complex task to combine the operational demands and the power system properties in an optimal manner. The EMS can therefore be seen as the ship's energy systems' orchestrator.

In this document, the functions for orchestrating the operational configuration are allocated to a higher level controller and the individual functions are separated in a power control hierarchy (see Figure 2). In this figure, the role of Damen as overall system integrator is additionally shown, where increased involvement and responsibility is seen in higher layers.

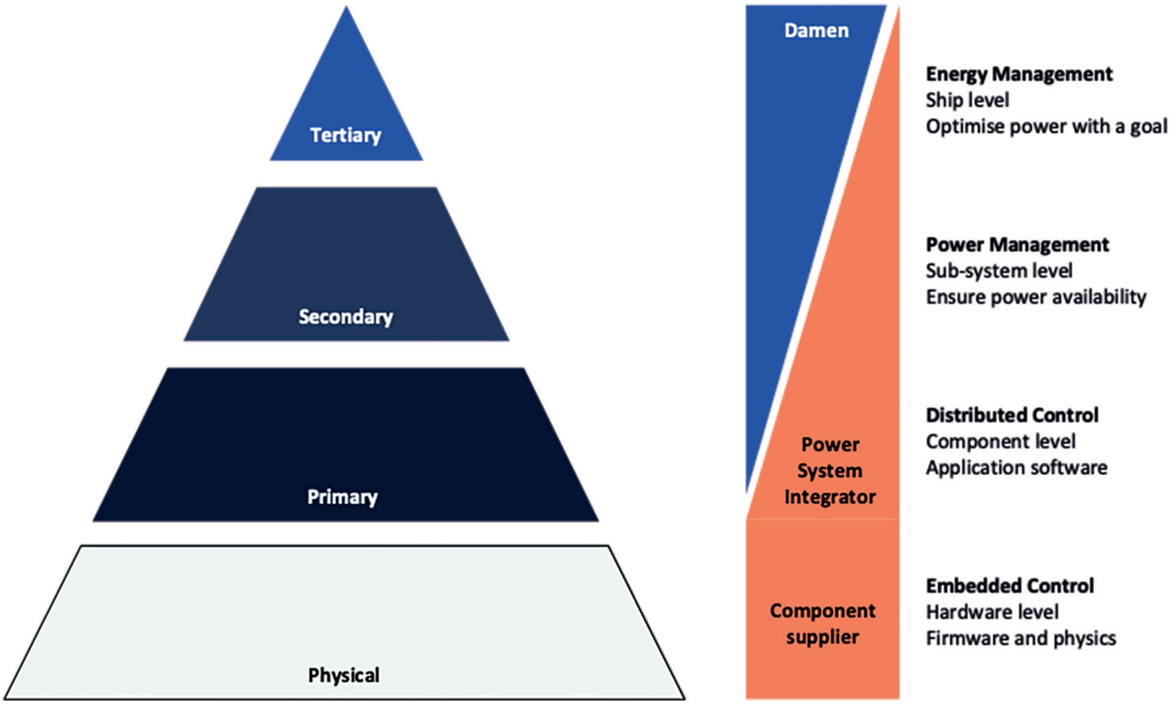

Figure 2. Hierarchical control layer responsibilities and the level of interest for Damen as ship builder.

These separations are not necessarily hardware based, but rather should be considered functional in nature. This proposed layering of power and energy control is a well-established control method. Power generation control in the land-based electric power grid uses the same layers, while this method and structure for maritime hybrid systems is well described in [1].

Adding an extra top-level control layer, instead of embedding the higher level optimization in the power management, has several advantages. First of all the functional tasks are clearly separated and kept distinct. The PMS has a clear task to ensure power availability (prevent blackouts), while the EMS has an operational optimization goal. Secondly the EMS is more independent from the actual physical system configuration than the PMS. By separating the layers, the EMS can be developed as a general solution, while the PMS is much more product or project specific.

For Damen as ship designer and builder, the third advantage is that Damen can develop the higher level operational performance in the EMS, while the lower level PMS can be delivered by the electrical system integrators. This also allows for upgrading the high-level EMS after delivery without changing the essential and certified lower-level PMS. The higher level control determines and defines the operational behaviour of the vessel and is thus closely related to the ship operational philosophy determined at design stage.

In this paper, the proposed three-level control hierarchy is explained. The overall concept is shown in Figure 3 for a conceptual hybrid power supply system. The three power and energy control layers are indicated, together with the propulsion control system as a secondary layer controller. This highlights the applicability of the hierarchical concept as a ship system-wide setup according to the separation and segregation of functions. For each level the responsibilities and functions will be defined, and standard interfaces between the layers described.

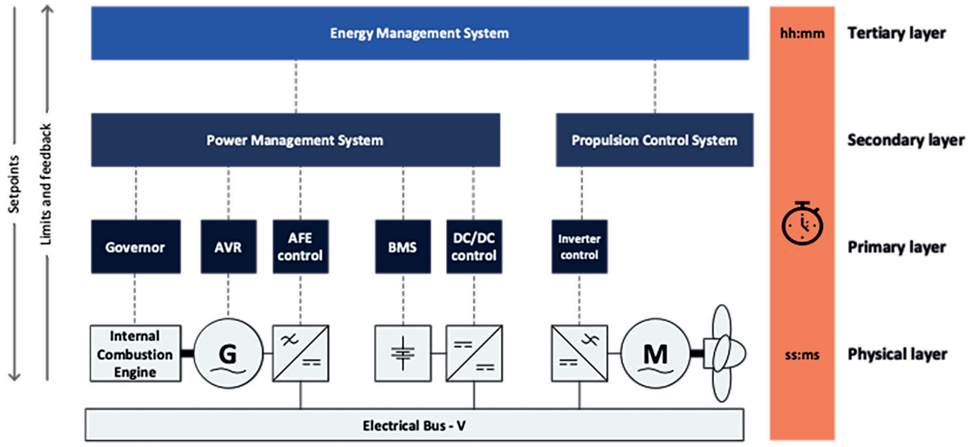

Figure 3. Power and energy control layers for a conceptual hybrid DC power supply system.

Hierarchical roles and responsibilities

In a hierarchical setup, each control layer needs to have well-defined roles and responsibilities. The overall philosophy is that lower control layers are closer to the physical hardware, and are responsible for component protection and determining limits. Limits (e.g. power available limit) are communicated upwards to higher level controllers, while higher level controllers issue commands. These commands and setpoints can be overruled by lower levels in case of conflicts or limit violation. The higher the level, the broader the scope of control and the lower the criticality of the system, while the time scales of the associated controllers are faster at lower layers, with the primary layer controlling the real-time hardware. These are summarized:

Tertiary layer - Energy Management (EMS)

- Non-critical control layer for power availability – no blackout when system fails or is not available

Secondary - Power Management (PMS)

- Orchestrated by EMS but can overrule EMS commands
- If EMS fails - PMS fall back to (predefined) configuration/ mode where system is suboptimal but stable.
- Essential control layer – in case of failure, power system runs in degraded mode but power availability is limited
- Optional manual control by human interface

Primary - Distributed control

- Regulated by PMS but can overrule PMS commands
- If PMS fails: system stays alive and components remain in (non-compensated) droop mode
- For critical signals, communication between different component controls is possible

Controller functionalities

In this section the primary functionalities of the three control levels are explained in the context of a DC power system.

Primary control

At the primary layer, control loops operate in the millisecond domain and are typically the lowest layer of control available to the user. The primary controller is an essential controller typically supplied by the component supplier and is an integral part of the device. The main goal at primary control is to regulate to setpoints and protect the component. This control is a distributed controller which is embedded within each component and is thus an integral part for its functioning. The following are the main functions of the primary layer.

1. Decentralised load sharing for sources

In order to ensure stable power supply without higher level communication for sources, load sharing is handled at primary level, typically using voltage droop for DC systems and frequency and voltage droop in AC systems. Droop makes use of a common quantity in the distribution network which is (nearly) equal for all connected devices to implicitly communicate the state of the grid. Based on a preconfigured relation, the source will adjust its power output based on the common quantity, illustrated in Figure 4. By adjusting the droop line vertically up or down (adjusting the frequency or voltage reference) load can be shifted between sources, according to the new consequent balance point.

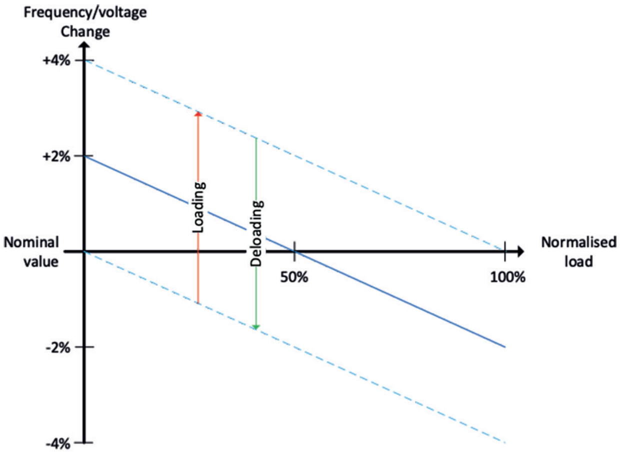

Figure 4. Droop lines description.

This makes for a robust and stable sharing of load between parallel sources, even with different dynamics or ratings. Table 1 gives some examples of primary control quantities and the regulator in question. It is worth noting that droop is also applicable to mechanical systems and is also used to facilitate running of multiple motors on the same shaft.

Table 1. Examples of primary control quantities and typical control devices.

Distribution network type	Control parameter	Typical control devices
AC electrical grid	Frequency (active power) Voltage (reactive power)	Engine governor Alternator AVR
DC electrical grid	Voltage	AFE DC voltage controller
Rotational mechanical system	Shaft speed	Engine governor Motor speed

2. Load regulation for consumers

Similarly to voltage droop for source control, the common quantity can also be used by consumers to communicate the network state without requiring higher level communication. Smart consumers can interact with the grid to adjust their power consumption and support the grid. This is illustrated graphically for various sources and consumers in Figure 5.

In this approach, piecewise linear droop characteristics are used to regulate consumers as well as ensure stable load sharing. Consumers can reduce power based on pre-specified network load levels being reached, while sources can in this way also supply constant power based on limits. Charging of energy storage systems is similarly controlled in the upper portion of the droop control parameter (f/V). Further details are explained in [2] and [3].

In power electronic converters, the load reduction is typically governed by the undervoltage regulator, a fast-acting control loop based on the DC voltage level. This coordination of load reduction based on voltage is also the principle in load prioritization in upcoming DC grid protocols such as ODCA and CurrentOS, where higher priority consumers will reduce load at a lower DC voltage than lower priority ones.

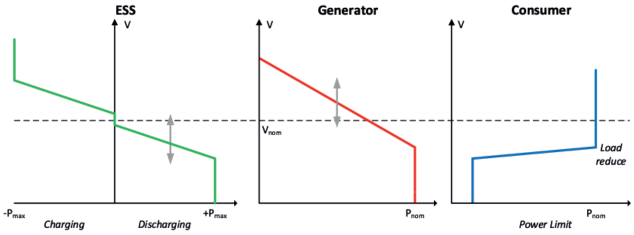

Figure 5. Example of droop lines for different types of components connected to an electrical network.

3. Maintain operation within component safe operating envelope

Another main goal of primary control is to ensure that the component is maintained within its safe operating limits.

This lower level protection can be active by regulating to a limit, or passive by communicating an alarm or limit value to a higher level controller. A typical example of this functionality is showcased in Battery Management System (BMS) which actively monitors the battery system within its scope and issues a current limit to higher level controllers. This limit is based on a number of factors and quantities which are only available internally to the BMS. In case the component limits are not respected and the battery is exceeding the safe operating envelope, the BMS has full authority to operate final level protection and disconnect the battery. Similar functionality is realized by a variable speed generator where the power availability is dependent on speed and needs to be communicated to the PMS as available power.

The measurement and calculation of power (available and actual) is of particular criticality to the control system hierarchy. Any primary level controllers are responsible for measuring their own power but can also communicate this to higher level controllers. If the primary level power measurement is to be used for power control, the criticality of the communication as well as reliability and accuracy of the measurement need to be taken into account.

Secondary control

At the secondary control layer, the control loops operate in the sub-second domain. The main goal of this control is to ensure power availability (blackout prevention).

The secondary control level is responsible for ensuring power availability at the power distribution level in the seconds-minutes domain. Several control functions are implemented on this level:

1. Calculation of available power – determination of the power reserve based on available online sources, power limits and current consumed power
2. Load dependent start-stop (LDSS) of sources – based on available power reserve, additional sources are placed online or shutdown. In a system with no energy storage this would be the main function which determines the online sources
   - Running hour optimisation – An optimisation of LDSS would be to optimise and adjust the online sources based on running hours. This optimises maintenance and evens out source utilisation.
3. Sequence control – automated operations (preset or programmable) such as starting up or shutting down of sources
4. Breaker monitoring and control – protection devices (e.g. fuses and/or circuit breakers) are monitored for status as well as controlled (if applicable). Control is also linked to other functions such as interlocks, synchronisation etc...
5. Source load sharing control – By adjustment of references, load on different sources can be adjusted according to the selected scheme e.g. asymmetric or proportional load sharing
   - Loading/deloading – load control as part of starting up and shutting down sequences
6. Voltage/frequency control – System voltage and/or frequency are controlled by the supervisory PMS to remain within nominal tolerances in steady-state conditions
7. Consumer control – In order to avoid blackout, (predefined) heavy consumers can be configured to request power availability before start up. In case of insufficient power reserve, a further source is brought online before starting up, with an interlock delaying consumer start.
   - Power limiting – typically associated with propulsion converters, this (continuous) power limit signal is used to constrain the maximum power that the propulsion can consume based on the available power reserve.
8. Load shedding – In order to avoid blackout, (predefined) consumers can be instantly tripped in case of insufficient power reserve.
   - Fast Load Reduction – typically associated with propulsion converters, this fast acting signal triggers an instantaneous controlled reduction in power in controlled loads.
9. Blackout start – starting up from a de-energised state requires a series of sequences to power up the system to a predetermined configuration. Backup auxiliary power (e.g. 24V) is typically available to initiate the base sequences.

Tertiary control

At the tertiary layer, the operating setpoints for the power related systems are determined for a particular operational goal. This operational goal depends on the operational state of the vessel and the system philosophy of the ship power system.

The EMS can be implemented in many ways, from a simple rule-based scheme up to a very intelligent algorithm. This implementation is not part of this guideline. The setpoints are issued to the secondary layer which then follows them and issue references to the primary layer to meet the setpoints if possible. The EMS operates on the minutes to hours domain and is not essential from a criticality point of view (system will remain stable in case of EMS failure) but can be considered essential for ship operations (e.g. meeting an operational goal). The main functions can be defined as:

1. Operate power system in line with system philosophy goals
   - E.g. operate in hybrid generation mode or mode dependent strategy
2. Determine operating setpoints for the power system
   - Source setpoints for optimized adjustment of load sharin
   - Setpoints for optimized charging
3. Address objective(s) for power system
   - E.g. fuel consumption, running hours, ESS cycling, noise signature etc...
   - Multiple or single objectives can be taken into account.

Conclusions

This paper has described a structured way of separating control functions in power supply control. For a shipbuilder this hierarchical layering allows better scoping of responsibilities and packaging of systems. In this way different strengths can be leveraged for each control layer, without affecting the functioning of each control system. This approach has now been implemented successfully on multiple vessel designs, each with different power system components, a common PMS platform and dedicated EMS for each application. This has maximised the platform approach, allowing reuse of the core PMS while allowing the EMS to be optimised. «

[1] *Geertsma, R.D., Negenborn, R.R., Visser, K. and Hopman, J.J., 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy, 194, pp.30-54.*

[2] *Che, Y., Zhou, J., Lin, T., Li, W. and Xu, J., 2018. A Simplified Control Method for Tie-Line Power of DC Micro-Grid. Energies, 11(4), p.933.*

[3] *Unamuno, E. and Barrena, E.A., Hybrid AC/DC Microgrid Mode-Adaptive Controls. Development and Integration of Microgrids. InTech, 2017.*