

A stylized graphic of a ship's hull and wake. The hull is dark blue with a light blue stripe, and the wake is white. The background is dark blue with a pattern of diagonal lines.

FLEXSHIP short course

Session 4

DATE

6/10/2025

FLEXSHIP

Season 4

Energy Management and Operational Optimization



Table of contents

1. **Energy management system**
 - Rule based methods
 - Optimization methods
2. **Battery management system**
 - Estimation of SOC and SOH
3. **Conclusion**



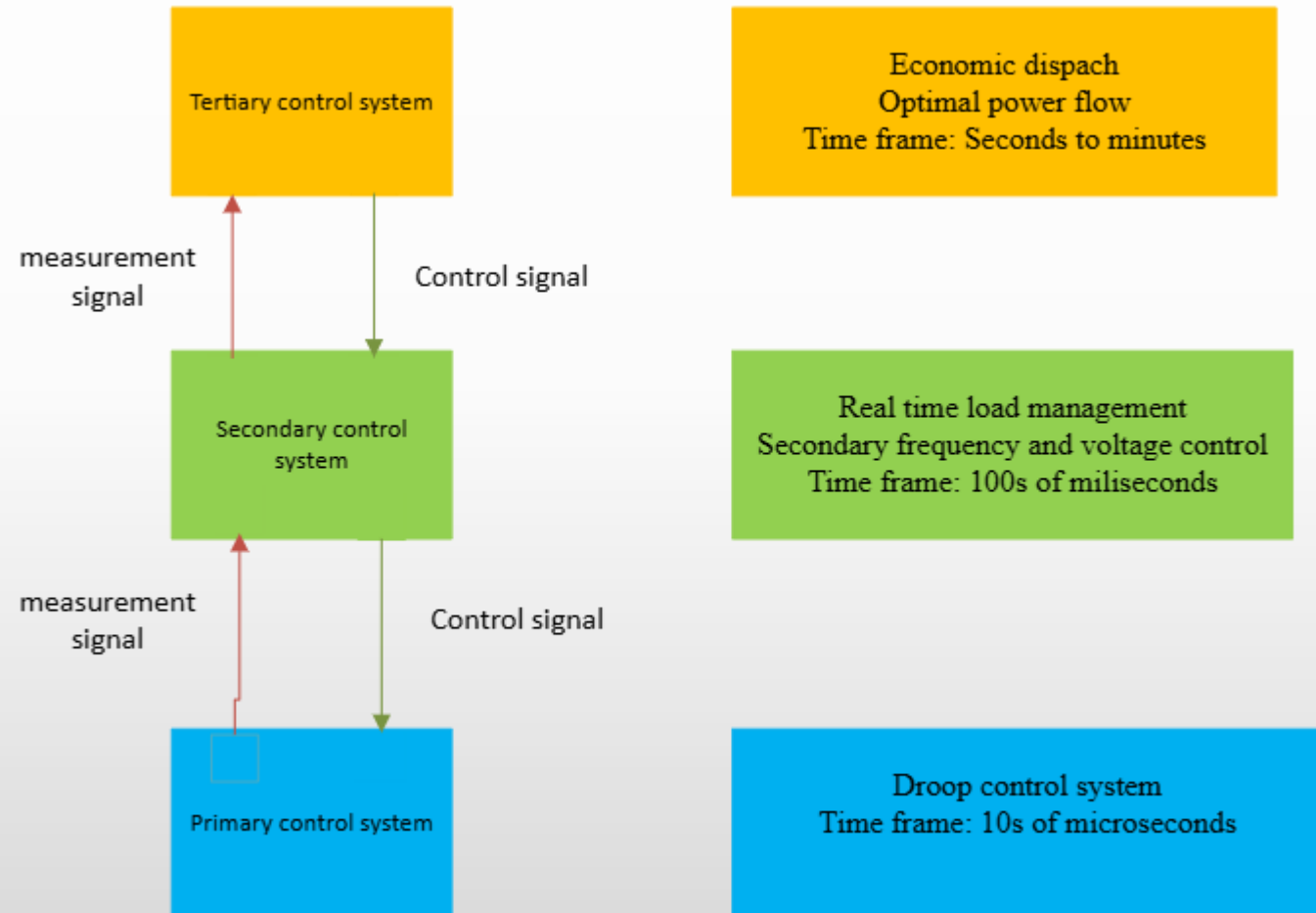
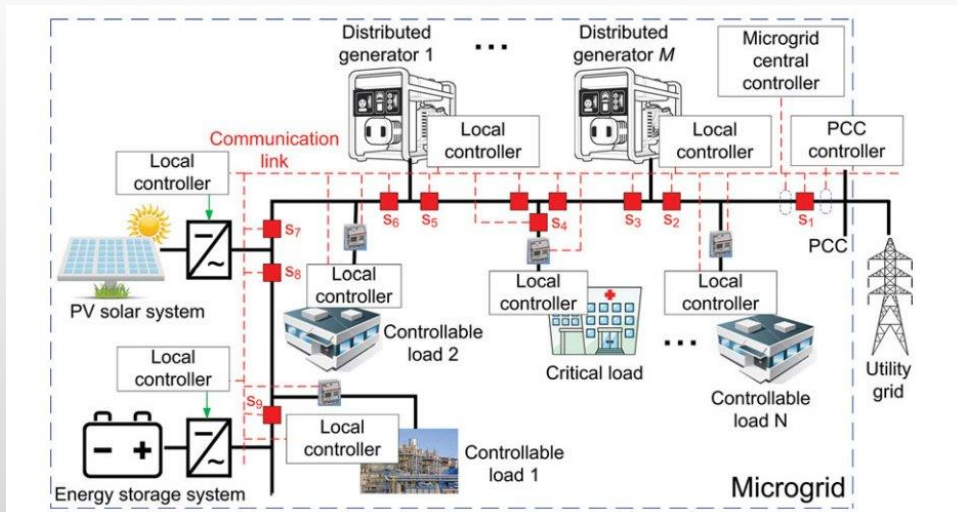
Table of contents

1. **Energy management system**
 - Rule based methods
 - Optimization methods
2. Battery management system
 - Estimation of SOC and SOH
3. Conclusion

1.1 The structure of hierarchical controller

There are three main layers for hierarchical control system

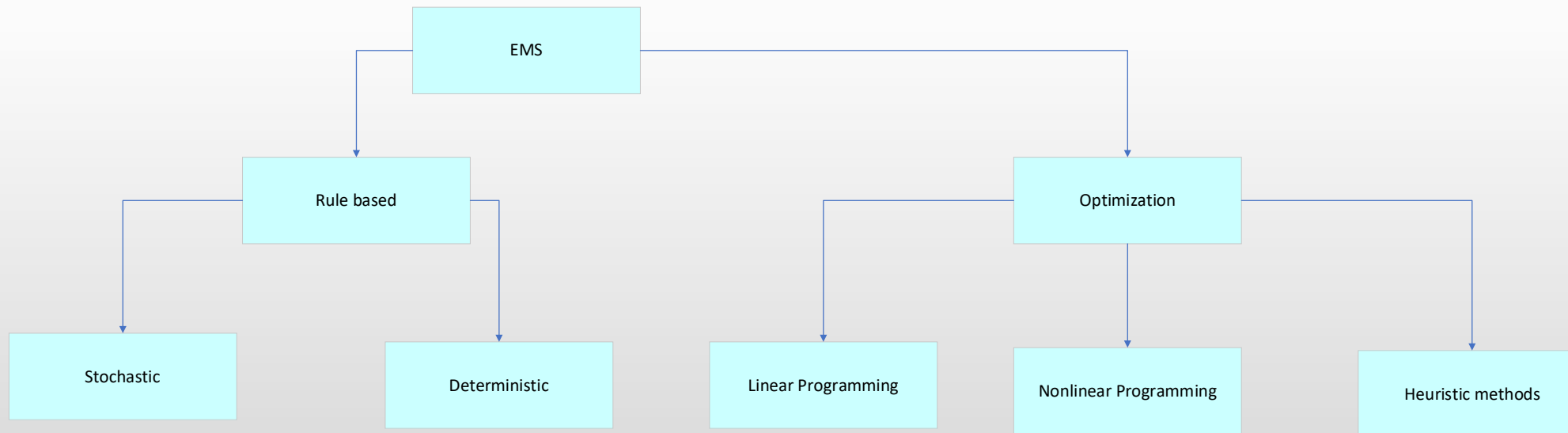
Tertiary control system
Secondary control system
Primary control system



1.2 Energy management methods

Centralized controller

- EMS is responsible for fuel consumption and decarbonization of hybrid ships.
- The output of EMS is the power setpoint of each genset and energy storage system
- There are two main approaches on EMS power setpoint design





1. Energy Management and Operational Optimization

FLEXSHIP

1.3 Rule based methods



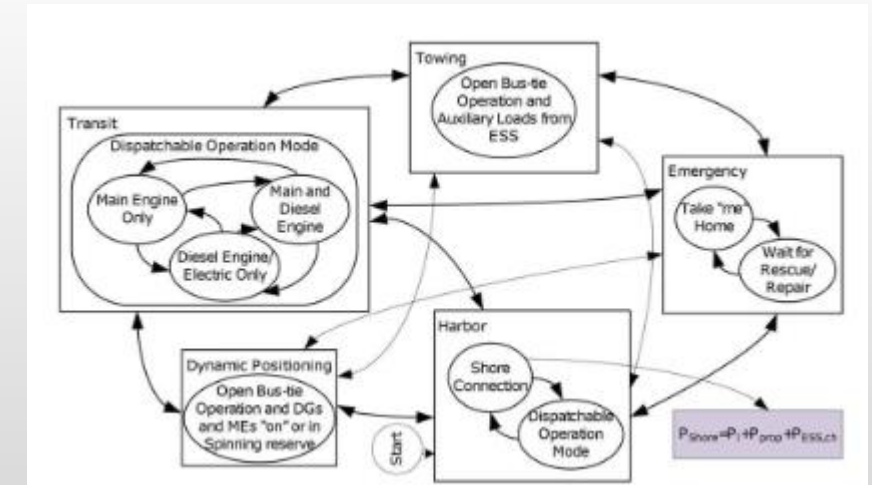
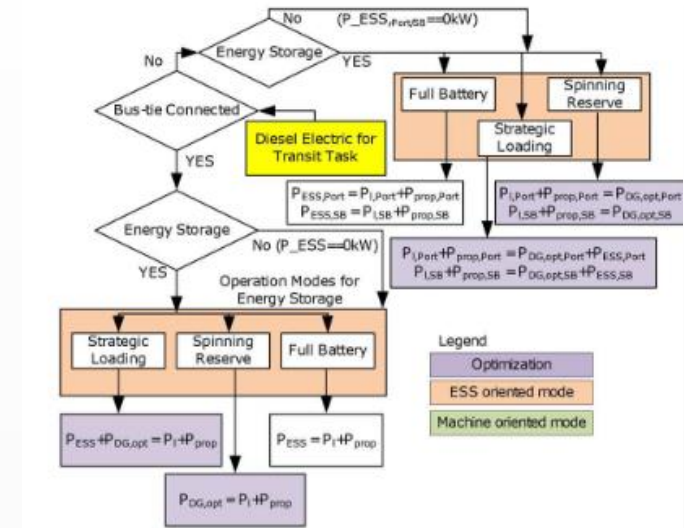
NTNU

Rule based methods for EMS design

- Rule based approaches are based on a set of IF-Then rules
- All the operating modes are established in the rules
- The operating condition depends on the current status of vessel.

Some operating modes are summarized below:

- Transit
- Towing
- Dynamic positioning
- Emergency
- Harbour



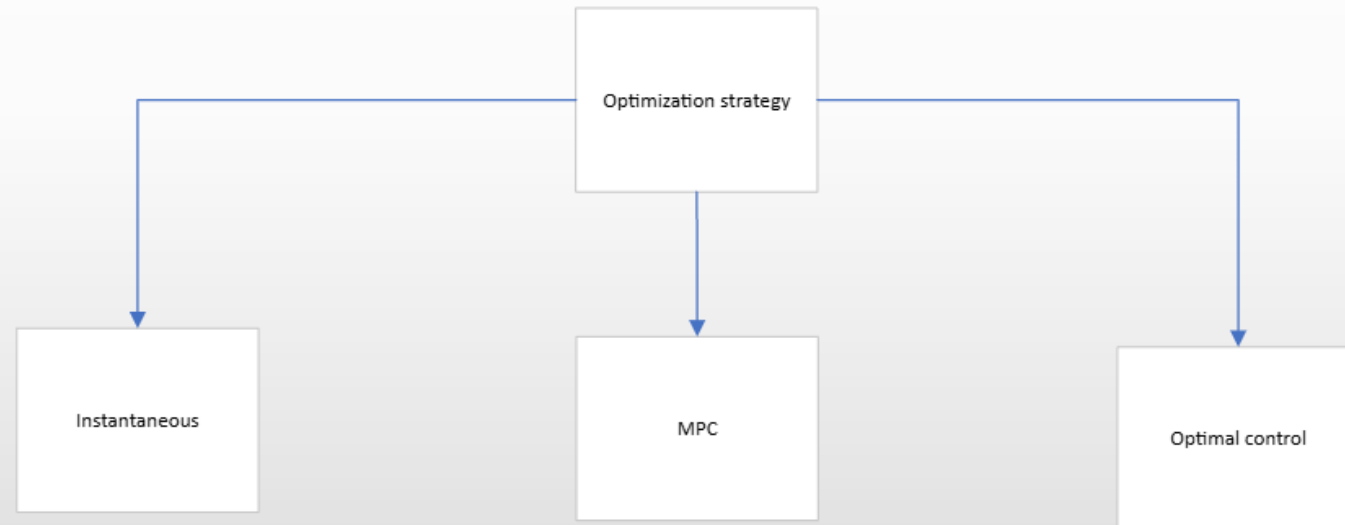
Ref.: <https://doi.org/10.1049/iet-gtd.2020.0668>

1.4 Optimization approach

Energy management can be represented as an **online optimization** problem.

Online optimization can be categorized into **three** types:

- Instantaneous Optimization
- Model Predictive Control (MPC)
- Optimal Control



1.4 Optimization methods

The optimization methods can be categorized to **linear program** or **nonlinear program**.

Linear programming is defined in the following format

$$\min C^T X$$

Subject to:

$$AX \leq b, X \geq 0$$

Where $C^T X$ is called the objective function. $AX \leq b$ and $X \geq 0$ are the constraints and the primary goal is designing the optimal X to minimize the objective function while satisfy the constraints.

1.4 Optimization methods

Two popular approaches to solve linear programs are [Simplex](#) and [Interior point methods](#).

In linear programming, the feasible region is known as a *polytope*. The corners, or extreme points, of this polytope are called *vertices*. It can be shown that if a linear programming problem has a feasible solution, the optimal solution lies at one of these vertices. The **Simplex method** is based on this principle—it systematically searches among the vertices of the polytope to find the global minimum.

On the other hand, interior point methods, use barrier functions or logarithmic potential functions to avoid violating barriers.

Interior point methods use [Newton methods](#) or [gradient base methods](#) to find the local minima.

1.4 Optimization methods

Nonlinear programming is another type of optimization method, defined as below:

$$\begin{aligned} &\text{Minimize: } f(X) \\ &\text{Subject to: } g_i(X) < 0, i = 1, 2, \dots, m \\ &\quad \quad \quad h_j(x) = 0, j = 1, 2, \dots, p \end{aligned}$$

Where $f(X)$ is the objective function and g is the inequality constrain set, and h is the equality constrain set. The main challenges in solving nonlinear programs are listed below:

- Most NLPs are not solvable. By solvable we mean to have sufficient conditions to reach the global minima. In this viewpoint, only a few nonlinear programs, that called convex program can be solved.
- In some applications, the objective function is not differentiable.
- In functions with a vast amount of local minima, finding the global solution is challenging

1. Energy Management and Operational Optimization

1.4 Optimization methods

Method	Suitable For	Advantages	Disadvantages
Gradient-Based Methods	Smooth, convex problems	Simple, fast for small problems	Can get stuck in local minima for non-convex problems
Interior-Point Methods	Large-scale convex problems with inequality constraints	Efficient for large problems	May struggle with non-smooth or highly non-convex problems
SQP	Smooth, constrained nonlinear problems	High accuracy for smooth problems	Computationally expensive for large problems
Penalty Methods	Problems with complex constraints	Can handle a variety of constraints	May require tuning of penalty coefficients
Lagrange Multiplier/KKT	Problems with equality constraints	Clear theoretical foundation	Limited to problems with smooth, differentiable functions
Genetic Algorithms	Global optimization, non-convex problems	Can escape local minima, handles complex landscapes	Computationally expensive, requires tuning
Simulated Annealing	Global optimization, non-differentiable problems	Robust to local minima	Slow convergence, requires temperature tuning
Direct Search Methods	Non-differentiable problems	No need for gradients	Less efficient, may require many iterations
Convex Relaxation	Non-convex problems that can be approximated by convex ones	Computationally efficient	May not guarantee an exact solution

1.4 Optimization methods

Distributed Energy Management

Another topology is the **distributed** control system.

In the distributed controller, the local controllers communicate with each other to manage each zone.

The local controllers manage their own zones, while trying to reach the global objective.

Unlike the centralized controller, the distributed method is more resilience against faults in subsystems.

The computation time for energy management decreases significantly in distributed controller.

1.4 Optimization methods

Aspect	Centralized Method	Distributed Method
Architecture	Single central controller or processing unit	Multiple agents/nodes with local controllers
Decision Making	All decisions made at a central point	Decisions made locally with coordination or consensus
Scalability	Poor scalability as system size increases	Highly scalable due to decentralized control
Communication Overhead	High communication to and from central unit	Lower global communication; often local communication only
Robustness	Vulnerable to single point of failure	More robust; failure of one node doesn't affect the whole system
Complexity	Simple to implement and manage initially	More complex due to distributed algorithms and synchronization
Computation Load	Central node handles all computation	Load is shared among nodes
Latency	May suffer from delays due to central bottleneck	Potentially faster with parallel local processing
Example Applications	Traditional control systems, data centers	Smart grids, multi-robot systems, sensor networks
Implementation Cost	Lower initial cost, but high for large systems	Higher initial setup, but cost-effective at scale
Adaptability	Less adaptable to dynamic changes in the environment	Highly adaptable due to local autonomy

ADMM for distributed controller

ADMM is a popular method for distributed control systems. Suppose we have two convex functions, $f(x)$ and $g(z)$. The objective is to minimize the summation of these two functions.

$$\begin{aligned} \min_{x,z} \quad & f(x) + g(z) \\ \text{s.t.} \quad & Ax + Bz = c \end{aligned}$$

It can be shown that the solution converges to the following iteration pattern

$$\begin{aligned} x^{k+1} &= \operatorname{argmin} (f(x) + \frac{\rho}{2} \|Ax + Bz^k - c + \lambda^k\|), \\ z^{k+1} &= \operatorname{argmin} (g(z) + \frac{\rho}{2} \|Ax^{k+1} + Bz - c + \lambda^k\|), \\ \rho^{k+1} &= \rho^k + Ax^{k+1} + Bz^{k+1} - c \end{aligned}$$



Table of contents

1. Energy management system
 - Rule based methods
 - Optimization methods
2. Battery management system
 - Estimation of SOC and SOH
3. Conclusion

2.1 BMS structure

BMS structure

The Battery Management System (BMS) is a critical component of the battery control system, responsible for managing power flow and implementing charge/discharge strategies. Its key functions include:

- Thermal management and control of battery cells to ensure optimal operating temperature.
- Real-time estimation of the State of Charge (SoC), State of Health (SoH), and available power.
- Controlling charge and discharge processes based on commands received from the Energy Management System (EMS).
- Ensuring safety protection by monitoring for faults such as over-voltage, over-current, and thermal runaway.

SOC estimation

State of Charge (SOC) represents the **current charge level** of a battery compared to its maximum capacity. SOC is not measurable in real time

Methods for SOC estimation:

- Coulomb counting (integrating overtime)
- Open voltage circuit
- State-estimation methods
- Data-driven methods (Machine learning and deep learning)

SOH estimation

State of Health (SOH) represents the ratio between **current capacity** of a battery compared the rated capacity. SOH is not measurable in real time.

Method Type	Description	Pros	Cons
1. Direct Measurement	Lab-based tests (e.g., full charge-discharge cycle)	Accurate	Time-consuming, not real-time
2. Model-Based	Use equivalent circuit models (ECM) or electrochemical models	Real-time capable, interpretable	Requires accurate modeling
3. Data-Driven	Use machine learning or statistical methods (e.g., neural networks, PCA)	Adaptable, handles complex data	Needs large training datasets
4. Hybrid	Combine model-based and data-driven techniques	Balanced accuracy & adaptability	Implementation complexity

Thermal management

Why we need thermal management?

- **Safety:** Overheating can lead to thermal runaway, fire, or explosion.
- **Performance:** Battery efficiency and capacity degrade outside the optimal temperature range (typically 20–40°C).
- **Lifetime:** High or uneven temperatures accelerate aging, increase internal resistance, and reduce cycle life.
- **Fast Charging:** High charging rates generate more heat; efficient cooling is essential to prevent degradation.



Table of contents

1. Energy management system
 - Rule based methods
 - Optimization methods
2. Battery management system
 - Estimation of SOC and SOH
3. Conclusion

Regarding the hierarchical control system, the following conclusion is observed:

- **Hierarchical control** provides a structured, **modular**, and **scalable architecture** for modern ship operations.
- Enables safe and **optimal coordination** between multiple subsystems (e.g., propulsion, power, navigation).
- Facilitates integration of autonomous functions, adaptive control, and hybrid energy systems.
- Supports **energy efficiency**, mission reliability, and smoother human-machine interaction.
- Ideal for next-generation ships, including hybrid-electric, autonomous, and low-emission vessels.

Thanks for your attention!