Electrification of Rail and Sea Transportation

12 February 2021

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Agenda

- Introduction
- Electrification of Railways
  - ✔ METRO Rail
  - ✔ High Speed Rail
- Electrification of Ships
  - ✔ Commercial Fleet
  - ✔ Naval (Military) Fleet
- Summary
Electrification of Railways
Introduction to Railway Electrification

- Global market for railway line electrification was $12.38 billion in 2018, and will grow at ~4% per year by 2022
- Global electric locomotive market size is projected to reach $7.85 billion in 2023
- A total market size of 4,000 units in 2012 and ~6,000 in 2020
- Rail traction can be segmented into three main sub-applications:
  - urban vehicles (trams and metros),
  - regional and commuters (mostly Electrical Multiple Units, or "EMUs"), and
  - high-speed trains (Power cars and EMUs).

Sources:  
Electric Locomotives – Houston Area

- **Houston METRORail** (since 2004)
  - 2nd most-traveled light rail system in Southern US
  - 37 Siemens S70 and 39 CAF USA vehicles
  - 600 V or 750 V DC overhead catenary
  - ~80 kW (110 hp) traction motor – per tram

- **Texas Central Railway** (planned 2026)
  - High speed trains
  - Based on the N700 Series Shinkansen
  - Up to 205 mph → ‘Bullet Train’
  - Houston to Dallas in ~90 mins
  - All electric system, with steel wheels

Sources:  
N700 Series Shinkansen – Main Specifications

- 25 kV, 60 Hz AC input voltage; > 50 small motors for driving

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Series N700</th>
<th>Series 700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>14M2T</td>
<td>12M4T</td>
</tr>
<tr>
<td>Unit configuration</td>
<td>4 cars per unit</td>
<td>(Same)</td>
</tr>
<tr>
<td>Seating capacity</td>
<td>1,323</td>
<td>(Same)</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>Tokaido: 270km/h, Sanyo: 300km/h</td>
<td>Tokaido: 270km/h, Sanyo: 285km/h</td>
</tr>
<tr>
<td>Operating speed at curve (R2500m)</td>
<td>270km/h</td>
<td>250km/h</td>
</tr>
<tr>
<td>Starting acceleration</td>
<td>2.6km/h/s (Tokaido / Sanyo)</td>
<td>1.6km/h/s (Tokaido), 2.0km/h/s (Sanyo)</td>
</tr>
<tr>
<td>Weight (at capacity)</td>
<td>Approx. 700 tons</td>
<td>708 tons</td>
</tr>
<tr>
<td>Car length</td>
<td>Middle cars: 25,000mm, Leading car: 27,350mm</td>
<td>(Same)</td>
</tr>
<tr>
<td>Car width</td>
<td>3,360mm</td>
<td>3,380mm</td>
</tr>
<tr>
<td>Car height</td>
<td>Front end of the leading car: 3,500mm, Rear end of the leading car: 3,600mm, Middle cars: 3,600mm</td>
<td>3,650mm</td>
</tr>
<tr>
<td>Total power output</td>
<td>17,080kW</td>
<td>13,200kW</td>
</tr>
<tr>
<td>Nose shape</td>
<td>Aero Double-wing (10.7m)</td>
<td>Aero Stream (9.2m)</td>
</tr>
<tr>
<td>Bogie structure</td>
<td>Bolsterless bogie</td>
<td>(Same)</td>
</tr>
<tr>
<td>Equipment for riding comfort</td>
<td>Advanced semi-active suspension system for all cars</td>
<td>Semi-active suspension system for seven cars</td>
</tr>
<tr>
<td>Body inclining system</td>
<td>Air spring mechanism (1” inclining)</td>
<td>-</td>
</tr>
</tbody>
</table>

Sources: [http://www.railway-research.org/IMG/pdf/r.1.3.3.3.pdf](http://www.railway-research.org/IMG/pdf/r.1.3.3.3.pdf)
Electric Locomotives – Equipment

Sources:
https://library.e.abb.com/public/896cf517fcce4406b7a4facb6d6b7d0c/Traction_systems_high%20power_RevB_180916_web.pdf
N700 Traction Converter

AC 25 kV, 60 Hz

PWM converter

VVVF inverter

Traction transformer

Electric Locomotives – Architecture

Block diagram of conventional locomotive

Sources:
Electric Locomotives – Architecture

Power Electronic transformer (PET) with traction motors
Improved Transformer Core – ABB

Internal structure of the material

Amorphous steel
Disordered AMD

Conventional silicon steel
Ordered RGO

The absence of a crystalline structure enables easy magnetization, and combined with low thickness and high electrical resistivity helps to greatly reduce no-load core losses.

Comparison with maximum values from Commission Regulation (EU) N° 548/2014 with some example three-phase AM designs

<table>
<thead>
<tr>
<th>Rating (kVA)</th>
<th>No-load losses (W)</th>
<th>No-load losses (W)</th>
<th>Loss reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular Grain</td>
<td>Amorphous Metal</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>145</td>
<td>65</td>
<td>55 %</td>
</tr>
<tr>
<td>250</td>
<td>300</td>
<td>110</td>
<td>63 %</td>
</tr>
<tr>
<td>400</td>
<td>430</td>
<td>170</td>
<td>60 %</td>
</tr>
<tr>
<td>800</td>
<td>650</td>
<td>300</td>
<td>54 %</td>
</tr>
</tbody>
</table>

The feeding voltage for a DC system can be 1,500 V, 750 V or 600 V
Electrification of Ships
Introduction to Ship Configurations

Half of the last century

Steam Plants - Mechanical Propulsion

Present

2 strokes Diesel Engine Mechanical Propulsion
Electric Generators Electric Propulsion
Gas Turbines Mechanical Propulsion

Possible future

Electric Generators and New Generation Power Distribution - Electric Propulsion

Sources: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867
Advantages of Electrical Propulsion

- Superior dynamics (start, arrest, speed variation) offered by electric motors over the conventional diesel motors (or gas turbines);
- Possibility of accommodating electrical motors with more flexibility, installing shorter shaft lines, or even outer rotating pods (thus eliminating the rudder and improving maneuverability);
- Reduced fuel consumption due to the modulation of thermal engines running (the number of generators on duty is adjusted in order to keep them working at their minimum specific fuel oil consumption);
- Higher comfort due to vibration reduction (thermal engines run at constant speed, therefore vibrations filtering is much efficient);
- High level of automation of the engine rooms and related reduced technical crew manning.

Sources:  
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867
# Commercial Ship Specifications

![Typical cruise ship: Fincantieri Royal Princess.](image)

**ALL-ELECTRIC CRUISE SHIP (FINCANTIERI ROYAL PRINCESS), MOST SALIENT CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross tonnage [GRT]</td>
<td>142,000</td>
</tr>
<tr>
<td>Life Saving Appliances</td>
<td>Up to 5600 people</td>
</tr>
<tr>
<td>Passenger Cabins</td>
<td>1,780</td>
</tr>
<tr>
<td>Public areas [sqm]</td>
<td>40,000</td>
</tr>
<tr>
<td>Length overall [m]</td>
<td>330</td>
</tr>
<tr>
<td>Breadth at Waterline [m]</td>
<td>38.4</td>
</tr>
<tr>
<td>Maximum Draft [m]</td>
<td>8.55</td>
</tr>
<tr>
<td>Contractual Service Speed [knots]</td>
<td>22</td>
</tr>
<tr>
<td>Propulsion system</td>
<td>4 LCI converters (48 pulse reaction) on two propellers</td>
</tr>
<tr>
<td>Continuous Propellers Output [MW]</td>
<td>2 x 18</td>
</tr>
<tr>
<td>Main Generators output [MW]</td>
<td>2 x 21 + 2 x 18</td>
</tr>
<tr>
<td>Main switchboards voltage [kV]</td>
<td>11</td>
</tr>
<tr>
<td>Total aggregated cable length [km]</td>
<td>4,000</td>
</tr>
<tr>
<td>Total aggregated cableways length [km]</td>
<td>65</td>
</tr>
<tr>
<td>Secondary distribution switchboards</td>
<td>460</td>
</tr>
<tr>
<td>Installed circuit breakers</td>
<td>23,000</td>
</tr>
</tbody>
</table>

Sources: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867)
Commercial Electric Ship Architecture

Sources: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867
Naval Electric Ship MVDC Architecture (Radial)

Sources: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867)
Naval Electric Ship – Zonal Design

**SYSTEM PACKAGE:**
- Hardware
- Software
- Manpower

**Zonal Design:**
For capabilities that are required to survive, assign associated redundant Packages / Sub-packages such that loss of any 2 adjacent zones will leave sufficient functionality in undamaged zones.

**Goal:**
Make Survivability an “Open Loop” Design Process rather than a “Closed Loop” Process

Sources: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8069355](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8069355)
Naval Electric Ship – Survivability

- Provide capability to recover selected undamaged loads in a damaged zone.
  - Often requires redundant feeds.

- Which Loads to Select?
  - Non-redundant Mission Systems
  - Loads supporting damage control efforts

Sources: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8069355
Naval Electric Ship MVDC Architecture (Zonal)

Sources: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7530867
Naval Electric Ship – Power Requirements

Available power for the next 60-80 years? Invest in IPES to harness total available power? Sufficient power availability to support future force capabilities?

ZUMWALT Class (3 Ships DDG1000-1002)

83 MW Shared Power

IPES on FSC
+ Survivability
+ Flexibility
+ Warfighting Capability
+ Modularity

DDG 1000 IPS+
Some Ability to Upgrade
+ Survivability
+ Warfighting Capability

DDG 1000 Mod Repeat
Minimum Ability to Upgrade
+ Survivability

Critical Decision Point for FSC

Naval Electric Ship – Integrated Power Systems

**IPES Required to Access Total Ship Power**

Integrated Power System (IPS) Architecture:
Shares Propulsion Plant with Ship Service

**DDG 1000**

- Fuel
- Gas Turbine
- Generator
- Distribution
- Electric Motor
- Ship Service & Weapons

**Evolutionary Approach**

Integrated Power & Energy System (IPES) =
IPS + Shared Energy + Advanced Controls

**IPES Tactical Advantages:**

- Flexibility
  - Enable Undefined Future Warfare Capability
- Adaptability
  - Support Evolving Mission Requirements/Systems
- Survivability
  - Limit Casualty Impact and Speed Recovery
  - Whole Ship Power Backup
  - Maneuver on “Battery”
  - Engage Until Last Drop of Fuel Expended
- Endurance/Efficiency
  - Greater Range & Time on Station

Industry is currently implementing this concept, e.g. Siemens BlueDrive, providing similar benefits with a significantly smaller footprint, reduced weight, and lower operating costs.

Naval Electric Ship Requirements

**Future Power Demands**

**Increases in Power Requirement Aboard Ships**

**More Power**
Step Change Incremental Development of Power Generation vs. Increase in Power Requirement over Time

- Exponential Capabilities Growth

**Different Demand**
New Capabilities Demand Pulse and Stochastic Power

- Sensor Demand
- Weapon Demand
- EW Demand

**Current Available Power Aboard Ships Cannot Support Dynamic Loads**

Current Power Systems Cannot Support Evolving Power Demands

Sources:  
# Impact of Pulsed Load

## Hypothetical Specification of Innovative High-Power Weapon Systems

<table>
<thead>
<tr>
<th>High Power System</th>
<th>Required Power [MW]</th>
<th>Weight [t]</th>
<th>Occupied Surface [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar Area Surveillance</td>
<td>4</td>
<td>70</td>
<td>137</td>
</tr>
<tr>
<td>Radar Ballistic Missile Defense Surveillance</td>
<td>17</td>
<td>250</td>
<td>272</td>
</tr>
<tr>
<td>Rail Gun</td>
<td>60</td>
<td>152</td>
<td>110</td>
</tr>
<tr>
<td>Laser (Medium Power) Point Defense</td>
<td>2</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Laser (High Power) Missile Defence</td>
<td>60</td>
<td>65</td>
<td>297</td>
</tr>
</tbody>
</table>


Power Electronics Building Blocks (PEBB)

PEBB Control Layers


System Control
- operating mode determination
\( \geq 10 \text{ms} \)

Application Control
- overriding control & measurements
\( \approx 1 \text{ms} - 1 \text{s} \)

Converter Control
- PLL synchronization
- \( \alpha \beta \leftrightarrow dq \) Transformations
- \( id \) and \( iq \) current control
\( \approx 10 \mu \text{s} - 1 \text{ms} \)

Switching Control
- Modulator
- Converter switching logic
- 2\textsuperscript{nd} level protection
\( \approx 1 - 10 \mu \text{s} \)

Hardware Control
- Stack or module assembly
- Snubbers for safe commutation
- Gate drives & feedbacks
- 1\textsuperscript{st} level device protection
- A/D & D/A conversion
- Gate drive power supply
- Current and voltage sensors
- AC/DC power terminals
- Thermal management
\( \approx 0.1 - 1 \mu \text{s} \)

Sources: [https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4123477](https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4123477)
PEBB for MVDC (VTech - CPES)

PEBB 1000

SiC PEBB for 1-kV DC Bus
100 kW, 100 kHz, 98%, 108 W/inch³

PEBB 6000

PEBB 6000 H-bridge

3rd Generation CREE SiC MOSFET & CPES gate driver

Summary

• Increased electrification in railways and ships – high power in several cases, well over 10 MW

• Scope of higher efficiency, smaller size and reduced environmental burden

• ‘Electronic Transformers’ becoming popular

• Health analytics for power systems – growing trend of data-driven approaches and automation

• Machine learning based digital twin and design optimization becoming popular

Electrification: For improved mass transportation!!
UH Power Courses and Degrees

- Two certificate programs
- MSEE degree program with specialization in Power & Energy Systems
- Distant PhD program – reduced course requirement for experienced engineers
- All the below courses can be taken online!

**Power Electronics and Renewable Energy:**
- ECE 6305  Power Electronics Converters and Control
- ECE 6343  Renewable Energy and Distributed Power Generation
- ECE 6317  Adjustable speed Motor Drive systems
- ECE 6318  Power Converters: Modeling and Applications

**Power Systems and Smart Grid:**
- ECE 6326  Power System Analysis
- ECE 6327  Smart Grid Systems
- ECE 6329  Power System Protection, Monitoring and Control
- ECE 6334  High Voltage Electrical Substations Design and Architecture
- ECE 6343  Renewable Energy and Distributed Power Generation

Please visit – [http://pemses.ece.uh.edu/courses-offered/](http://pemses.ece.uh.edu/courses-offered/)
Thank You!

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(For more information regarding our laboratory, research, projects and PEMSEC Consortium, please visit: http://pemses.ece.uh.edu/pemsec/)