Shipboard Power Quality Problems: What it is, What Causes it, Effects of it, and Technologies to Correct it

Green Boats and Ports for Blue Waters IV
Portland, OR
August 29-30, 2018

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Shipboard Primary Power Quality

- **Power Factor**: Ratio of Real Power measured in kW (the power that does the actual work) and Apparent Power measured in kVA (the total power supplied to the system).

- **Harmonics**: Current/Voltage produced by non-linear loads (VFDs, Electronics, Pulsing Equipment, Inverters, lighting) resulting in distorted sinusoidal wave form.
  - Problem started a few decades ago and continues to get worse
  - Generators have limits of how much non linear loads can be applied

- **Proper Voltage and Stability**: Equipment will only perform at design output when operated on clean power at design voltage. Voltage instability is caused by mismatch in electrical system impedance between source and load.

- **Phase Balance**: Imbalance in 3 phase loads is when each phase carries a different amount of load; this usually occurs on single phase loads fed from a 3 phase transformer.

**Power Quality Rating (PQR)**: Calculated metric using: Power Factor, Harmonics, Imbalance
Shipboard Power Quality Components

- Power Factor: Ratio of Real Power measured in kW (the power that does the actual work) and Apparent Power measured in kVA (the total power supplied to the system).
  - Real Power usage is directly proportional to generator fuel consumption
  - Reactive Power is magnetizing current needed to operate inductive devices
  - Power factor of 1 is best: resistive heating, incandescent lights
  - Low Power Factor caused by: inductive motors, transformers, fluorescent lights
  - Low Power Factor causes increased current flow resulting in heat generation

- Shore Power Typically has a Cost Penalty for Poor Power Factor:
  - kVA or kVAR charge
  - Direct Fees for reactive current in some form
Harmonics

- Harmonics are dynamic
- Harmonics induce temperature rise in equipment and system
- Harmonics shorten equipment life and can cause failures
- Harmonics cause noise in electronic circuits
- Regulatory Bodies usually have a 5% max THD at a Common Junction Point

220 VAC Lighting Panel on Ship
Harmonics

- Cause distortion to current sine wave
Harmonics

- Examples of distortion to current sine wave found on ships

3 Phase Lighting Panel

UPS Power Supply  For Engine Control System
Harmonics

- Create currents at whole number multiples of Fundamental Frequency

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>60</td>
<td>120</td>
<td>180</td>
<td>240</td>
<td>300</td>
<td>360</td>
<td>420</td>
<td>480</td>
<td>540</td>
<td>600</td>
<td>660</td>
</tr>
<tr>
<td>Sequence</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Sequence Rotation Effect

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Rotation</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Forward</td>
<td>Creates Heat</td>
</tr>
<tr>
<td>-</td>
<td>Reverse</td>
<td>Produces Counter Torque in Motors/Generators</td>
</tr>
<tr>
<td>0</td>
<td>None</td>
<td>Excess Current/Voltage in Neutral Wire</td>
</tr>
</tbody>
</table>

UPS Power Supply For Engine Control System
Voltage and Stability

➢ Improper Voltage Level or Stability
➢ Decrease Equipment Life and Waste Energy

460 VAC Motor operating on low voltage (down to 426 VAC or 7% below name plate value) which increases motor slip causing decreased chiller capacity

480 VAC Power Distribution Board Feed to HVAC Chiller
Voltage and Stability

- Voltage Variation Impacts Motor Performance

Table 2. General Effect of Voltage Variations on Induction Motor Performance (for General-Purpose Standard Efficiency Motors)

<table>
<thead>
<tr>
<th>Motor Characteristic</th>
<th>Voltage Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90% of Nameplate</td>
</tr>
<tr>
<td>Starting and Maximum Running Torque</td>
<td>-19%</td>
</tr>
<tr>
<td>Starting Current</td>
<td>-10%</td>
</tr>
<tr>
<td>Full-Load Current</td>
<td>+5% to +10%</td>
</tr>
<tr>
<td>Full-Load Efficiency</td>
<td>-1% to -3%</td>
</tr>
<tr>
<td>Full-Load Power Factor</td>
<td>+3% to +7%</td>
</tr>
<tr>
<td>Percent Slip</td>
<td>+22%</td>
</tr>
</tbody>
</table>

*Source: Institute of Electrical and Electronics Engineers (IEEE) Standard 141-1993.*
Voltage and Stability

- **Surges, Sags, and Transients:** Sudden inrush or drop in voltage
  - Equipment damage can occur when operating outside of the allowable design parameters
  - Sags usually caused by starting of large loads
  - Surge and Transients
    - Short Duration
    - Opening and closing of breakers on large loads
    - Lightning
Phase Balance

- Imbalance across phases results in increased energy consumption
  - Transformers efficiency declines from eddy currents and demagnetization
  - Load side can be effected by overdraw of power on one phase

Phase 1 has 60% greater current draw than Phase 3
Power Quality Rating (PQR): universal metric showing the efficiency of electrical energy flow.

- A PQR of 100% indicated that all energy was used for useful work.
- A PQR of 30% indicates that 30% was used for useful work and 70% was wasted (heat, vibration, etc.)

\[
PQR = \frac{\cos \frac{\varphi}{1+(THD_1)^2} L_1 + \cos \frac{\varphi}{1+(THD_2)^2} L_2 + \cos \frac{\varphi}{1+(THD_3)^2} L_3}{3}
\]
Poor Power Quality Summary

- Decreases Efficiency of Loads
- Decreases Efficiency and Capacity of Generators and Transformers
- Decreases Equipment Life and Reliability
- Causes Intermittent Faults
- Creates Noise in Electronic Equipment/Systems
- Reduces Performance of Radar, Sonar, Electronics, Motors, etc.
- Increases Heat Load on HVAC System

Bottom line: Poor Power Quality Wastes Energy and Money and Decreases the Vessel’s Overall Reliability
Shipboard Power Quality

- All ships have some power quality issues of some degree, so what do we do about it?
Traditional Power Quality Improvement Methods

- **Power Factor Correction**
  - Use capacitors to supply reactive load: Adds inefficiency in charge/discharge cycle, requires maintenance/replacement over time

- **Harmonic Correction**
  - Use Isolation Transformers: k-factor transformers are double size/cost
  - Use Inductors: typically tuned for specific harmonics, cannot change rapidly with harmonics

- **Phase Imbalance**
  - Mechanically shift loads: not always feasible

- **Proper Voltage and Stability**
  - Adjust voltage regulators and transformers for proper voltage
  - Use Transient Voltage Surge Suppression (TVSS): Capacity can be halved per event
New Technology: Software-Defined Electricity

A model based computing power electronics system that fully synchronizes electricity in real time

- Flash Energy Storage System: Proprietary transistor based injection/consumption energy storage system
- Task Oriented Optimal Computing: processes up to petabytes ($10^{15}$) of data a day
- Takes measurement at the nanosecond (one billionth of a second) and performs correction at the microsecond (one millionth of a second) level
- Digitally maps power network and identifies each load
Software-Defined Electricity
Shipboard Power Quality Improvement

- Power Factor Correction to Near 1
  - Reduces heat in motors, transformers, generators, wiring
  - Improves efficiency of motors, transformers, generators

- Harmonics corrected up to the 23\textsuperscript{rd}, measured up to the 53\textsuperscript{rd}
  - Eliminates transformer hum, increases capacity
  - Uses standard motors with VFD, no additional motor cooling required, no bearing issues
  - Improves electrical equipment reliability
  - Improves performance and reliability of electrical/electronic loads

- Balance three phase loads
  - Reduces transformer sizing and improves efficiency
  - Prevents overloading of one phase

- Real Time Voltage Surge Protection and Stabilization
  - Real time matching of system impedance
Software-Defined Electricity

Measurements with and without 3DFS Vector Q2 Software-Defined Controller

Measurements taken by Mike Gaffney at 3DFS facility

Without Vector Q2

With Vector Q2
Software-Defined Electricity

Power Quality Rating Improvement Upon Activation

7 cycle snapshot showing the moment the VectorQ2 was turned on

This image shows the moment that Electrical Correction begins improving the Power Quality Rating from 22% to 92%
Software-Defined Electricity Benefits

- Ground current nullified: removes noise to improve electronics performance (Radar, Sonar, Automation, Controls)
- Eliminates damaging stray currents
- Asynchronous motors will operate at name plate speed maintaining full performance of driven load
- Improves IT performance and reduces heat
- Identifies all energy consuming loads and monitors in real time
  - Performs predictive analysis on all electrical equipment
  - Provides energy consumption of each piece of electrical equipment
Software-Defined Electricity: Digital Map

Real time load analysis precisely identifies every load in the panel by constantly and exhaustively analyzing the electricity demand through a unique form of electrical signature analysis.

Each parameter has natural variations during normal use that create clearly defined boundaries for a real time baseline of consumption. A real time baseline provides instant awareness of any parameter deviation, during any phase of usage.

Real time load analysis is done automatically and the accuracy of the predictability enhances with time.
Electricity in the Modern World

Requires real time digital measurement and bidirectional flow control.

Energy Efficiency + Electrical Efficiency = Network Stability
Questions?

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