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

NAVIS
ENERGY MANAGEMENT SOLUTIONS LLC

Mike Gaffney CEM, CPQ, CEA
Senior Engineer
USCG Licensed Chief Engineer
Norfolk, VA 23502, USA

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

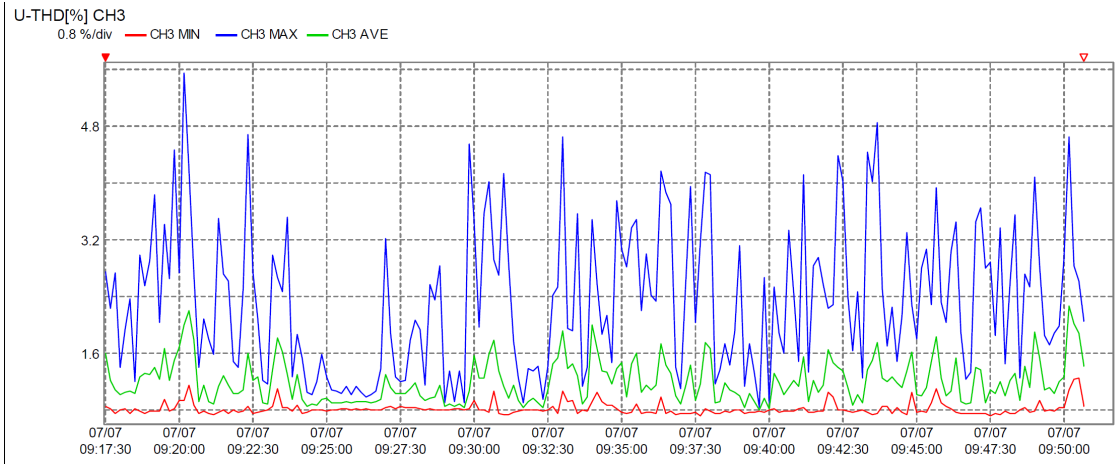
Shipboard Power Quality Components

- 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

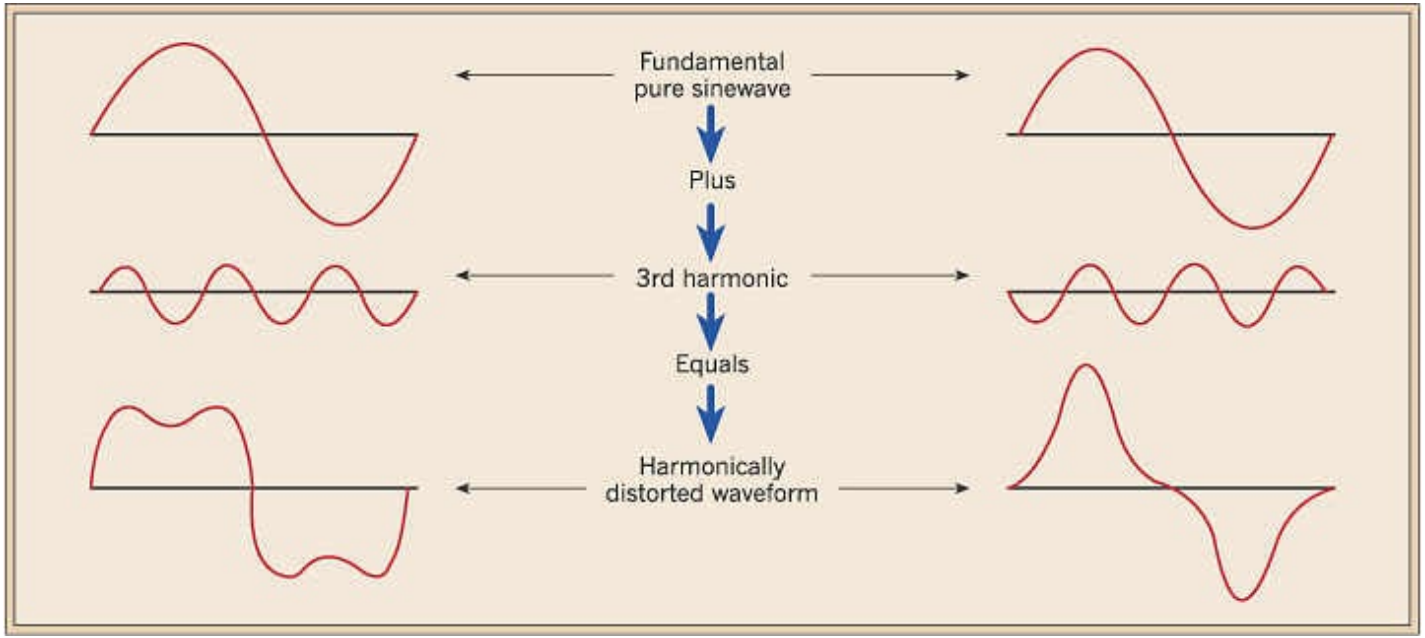
- Harmonics are dynamic
- Harmonics induce temperature rise in equipment and system
- Harmonics shorten equipment life and can cause failures
- Harmonics cause noise in electronic circuits
- Regulatory Bodies usually have a 5% max THD at a Common Junction Point



220 VAC Lighting Panel on Ship

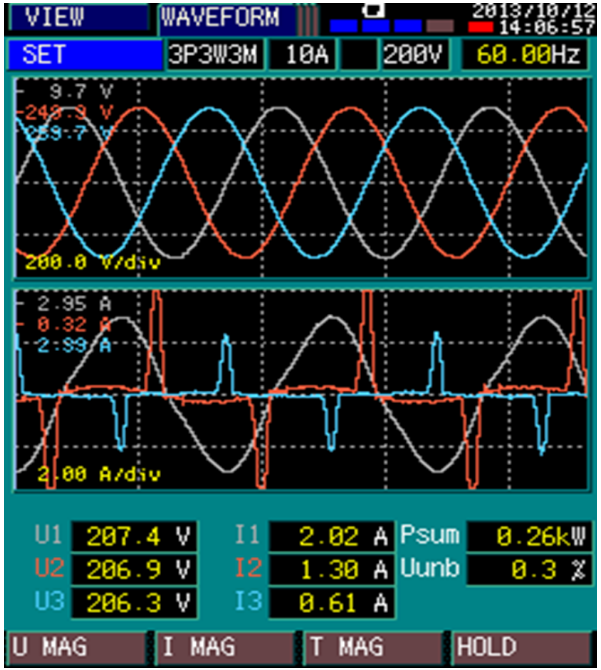
Harmonics

- Cause distortion to current sine wave

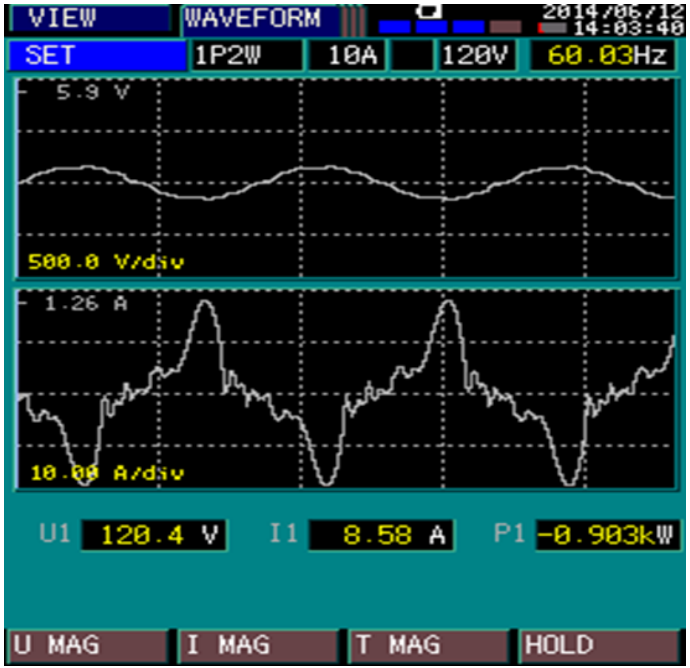


Harmonics

- Examples of distortion to current sine wave found on ships



3 Phase Lighting Panel

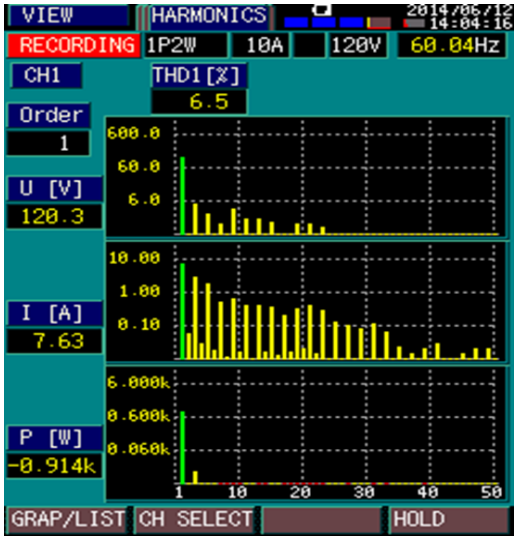


UPS Power Supply For Engine Control System

Harmonics

- Create currents at whole number multiples of Fundamental Frequency

Harmonic Order	1	2	3	4	5	6	7	8	9	10	11
Frequency	60	120	180	240	300	360	420	480	540	600	660
Sequence	+	-	0	+	-	0	+	-	0	+	-

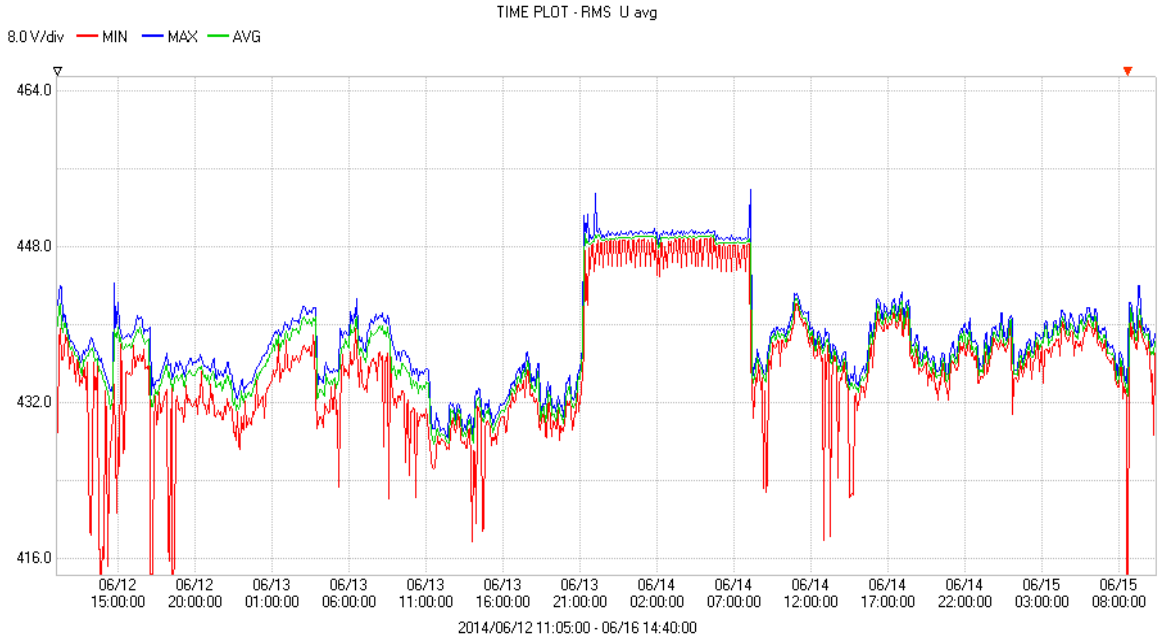


Sequence	Rotation	Effect
+	Forward	Creates Heat
–	Reverse	Produces Counter Torque in Motors/ Generators
0	None	Excess Current/Voltage in Neutral Wire

UPS Power Supply For Engine Control System

Voltage and Stability

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



480 VAC Power Distribution Board Feed to HVAC Chiller

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

Voltage and Stability

- Voltage Variation Impacts Motor Performance

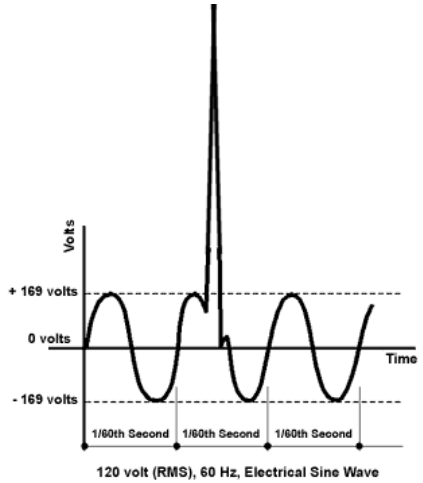
Table 2. General Effect of Voltage Variations on Induction Motor Performance (for General-Purpose Standard Efficiency Motors)

Motor Characteristic	Voltage Variation	
	90% of Nameplate	110% of Nameplate
Starting and Maximum Running Torque	–19%	+21%
Starting Current	–10%	+10%
Full-Load Current	+5% to +10%	–5% to –10%
Full-Load Efficiency	–1% to –3%	+1% to +3%
Full-Load Power Factor	+3% to +7%	–2% to –7%
Percent Slip	+22%	–19%

Source: Institute of Electrical and Electronics Enginners (IEEE) Standard 141-1993.

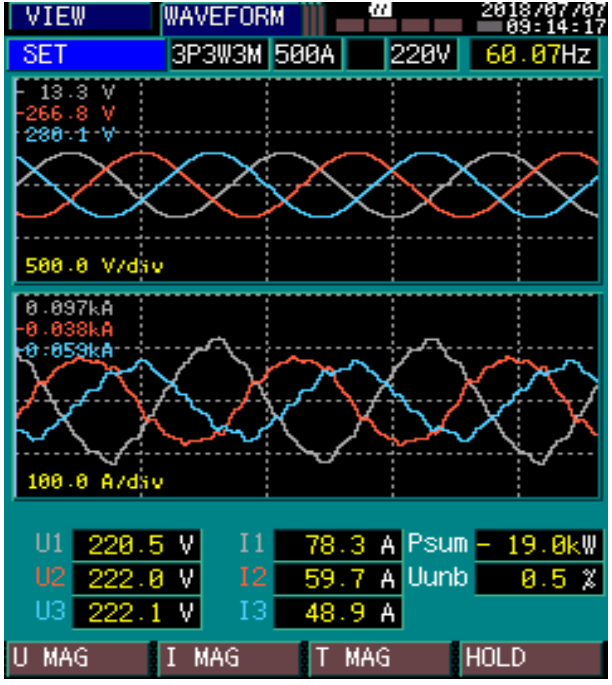
Voltage and Stability

- 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

$$PQR = \frac{\left(\frac{\cos\varphi}{\sqrt{1+(THD_I)^2} \times \sqrt{1+(THD_V)^2}}\right)_{L1} + \left(\frac{\cos\varphi}{\sqrt{1+(THD_I)^2} \times \sqrt{1+(THD_V)^2}}\right)_{L2} + \left(\frac{\cos\varphi}{\sqrt{1+(THD_I)^2} \times \sqrt{1+(THD_V)^2}}\right)_{L3}}{3}$$

- 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.)

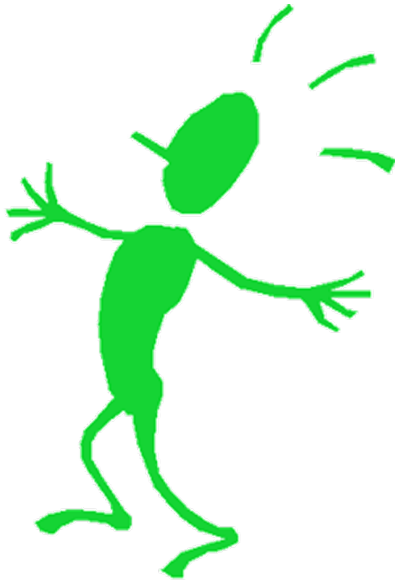
Poor Power Quality Summary

- 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

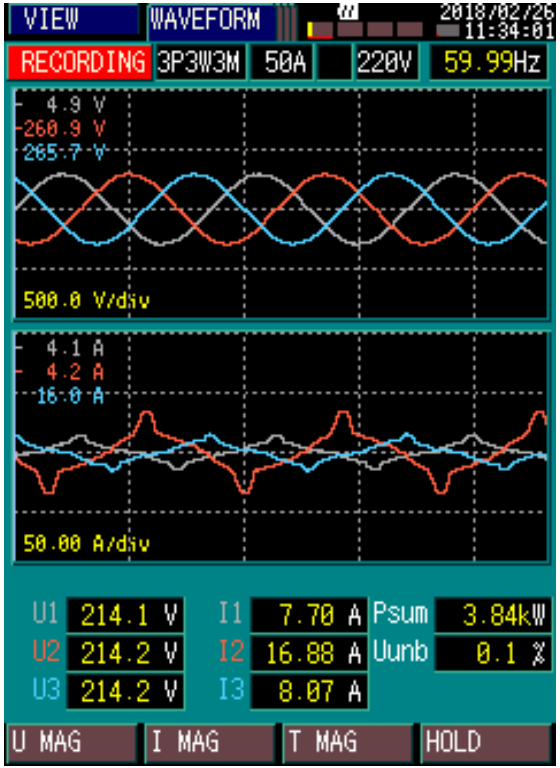
A model based computing power electronics system that fully synchronizes electricity in real time

- 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

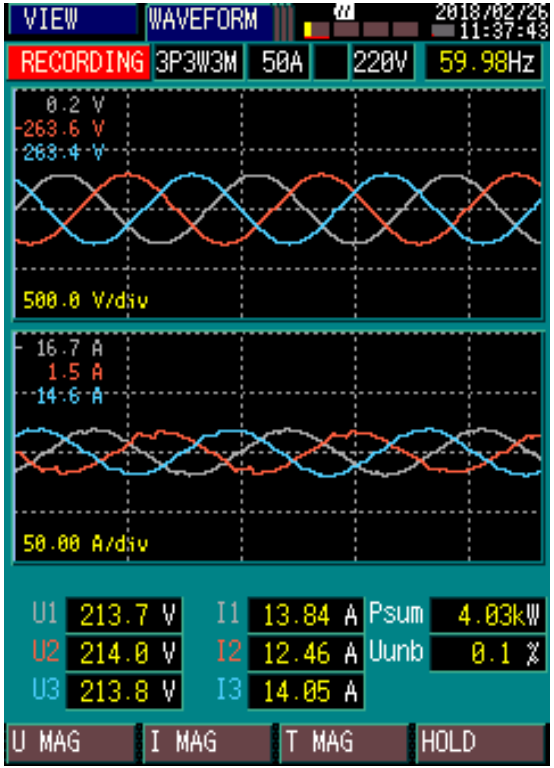
Software-Defined Electricity
Shipboard Power Quality Improvement

- Power Factor Correction to Near 1
  - Reduces heat in motors, transformers, generators, wiring
  - Improves efficiency of motors, transformers, generators
- Harmonics corrected up to the 23rd, measured up to the 53rd
  - 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



Without Vector Q2



With Vector Q2

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

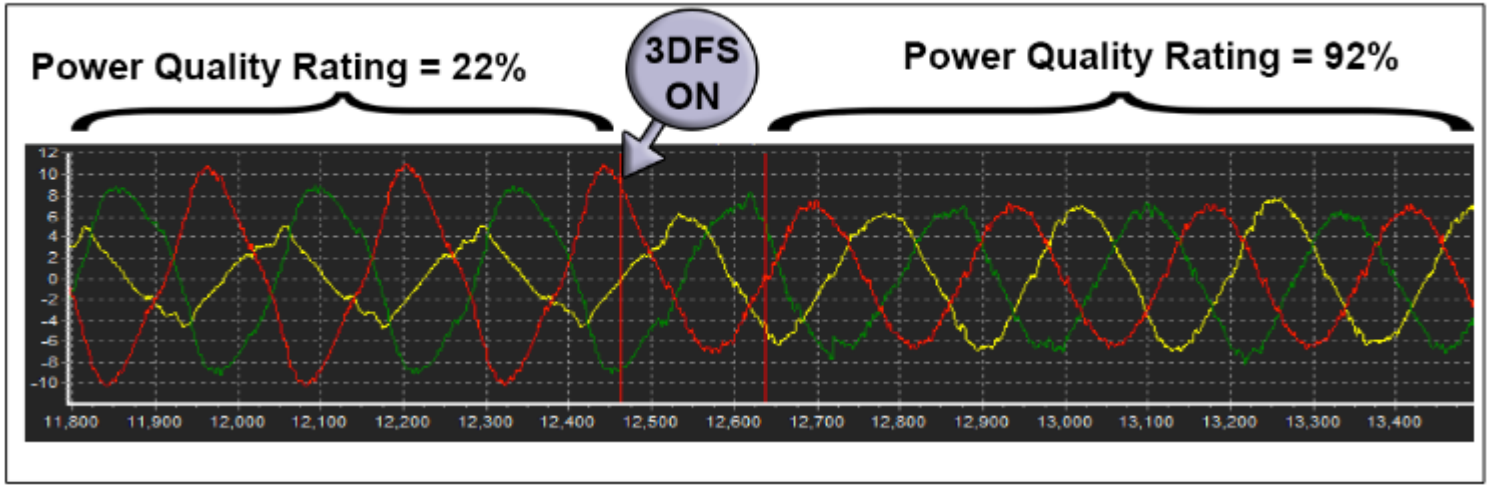
Measurements taken by Mike Gaffney at 3DFS facility

Software-Defined Electricity

Power Quality Rating Improvement Upon Activation

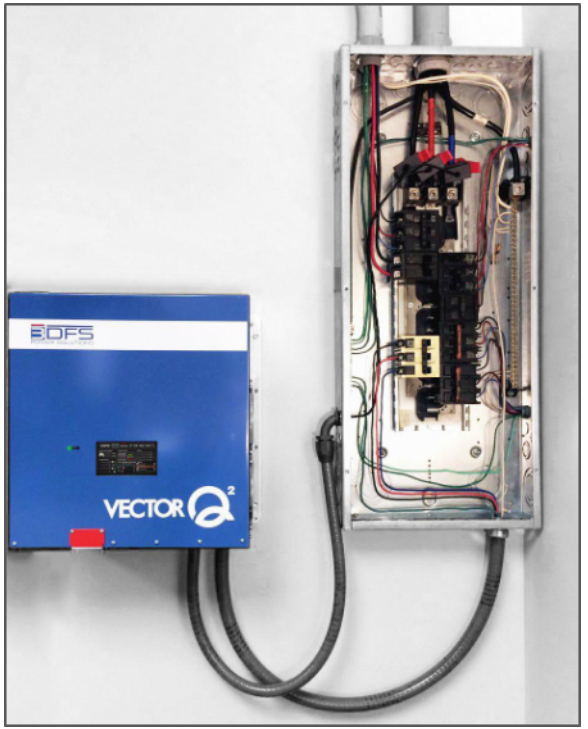
7 cycle snapshot showing the moment the VectorQ2 was turned on

This image shows the moment that Electrical Correction begins improving the Power Quality Rating from 22% to 92%



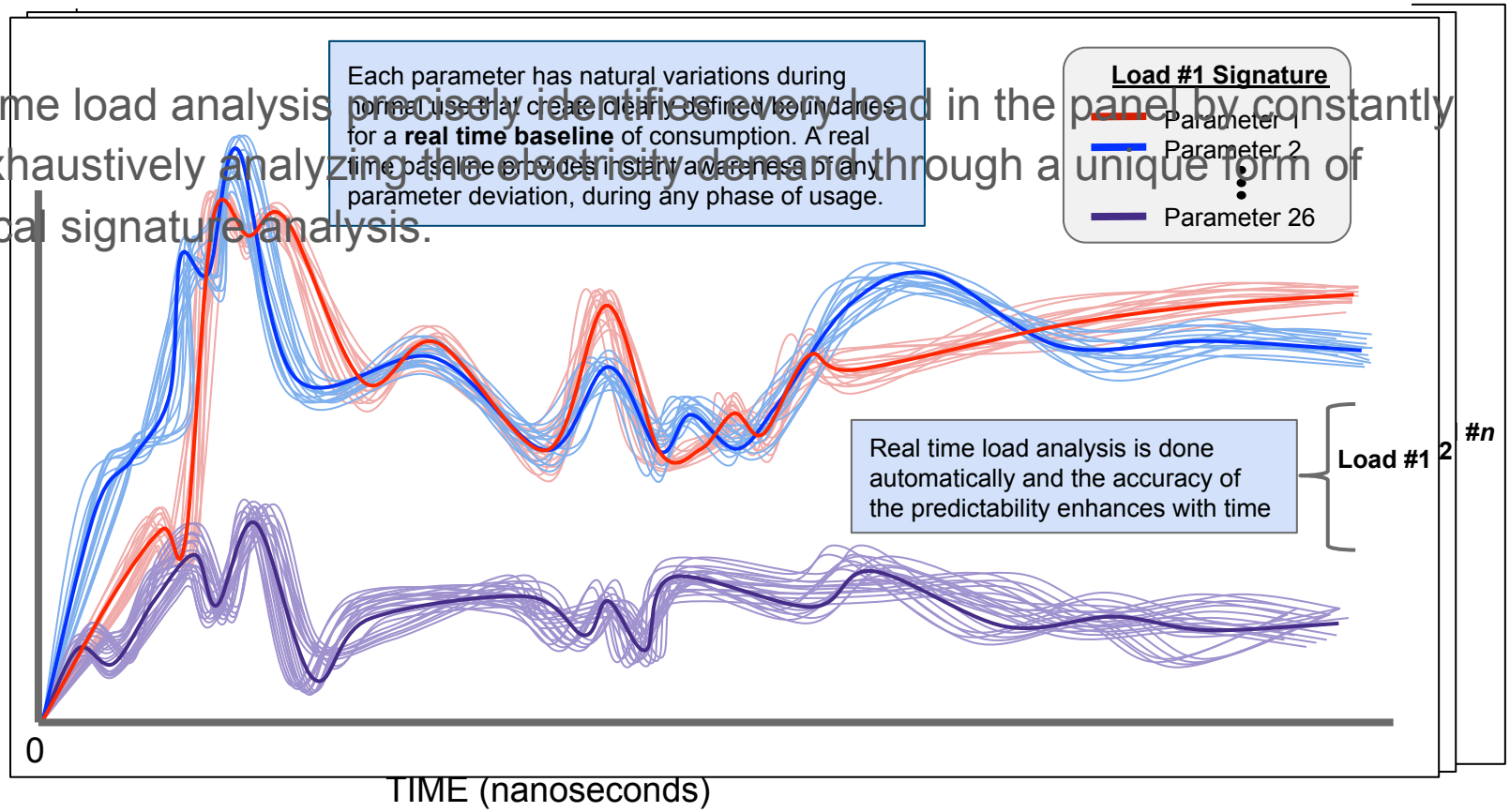
Software-Defined Electricity Benefits

- 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



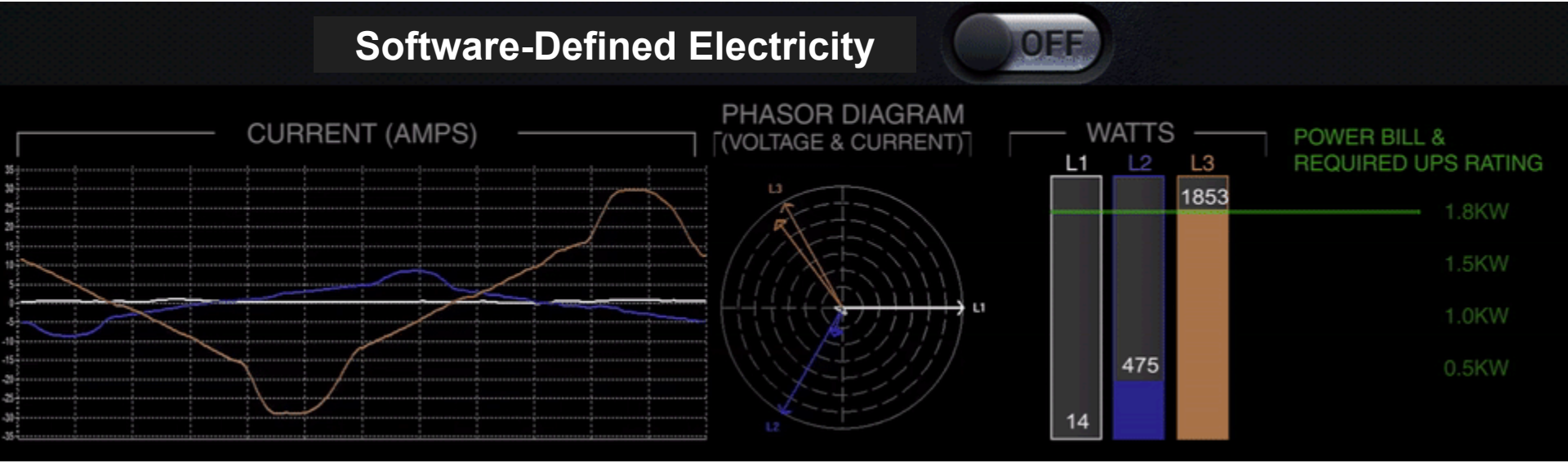
Software-Defined Electricity: Digital Map

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.



Electricity in the Modern World

Requires real time digital measurement and bidirectional flow control.



Energy Efficiency + Electrical Efficiency = Network Stability

Questions?

Mike Gaffney CEM, CPQ, CEA
Senior Engineer
USCG Licensed Chief Engineer
Norfolk, VA 23502, USA
(757) 289-5722
mgaffney@navisenergy.com

Chris Doerfler
3DFS.COM
919.807.1884
chris@3dfs.com