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VELCO

VELCO's Essex STATCOM

A Versatile Transmission Solution

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Grid of the Future 2017

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Abstract

Introduction

Project Overview

System Studies and Equipment Performance Validation

Construction Highlights

Recent System Performance

Conclusion

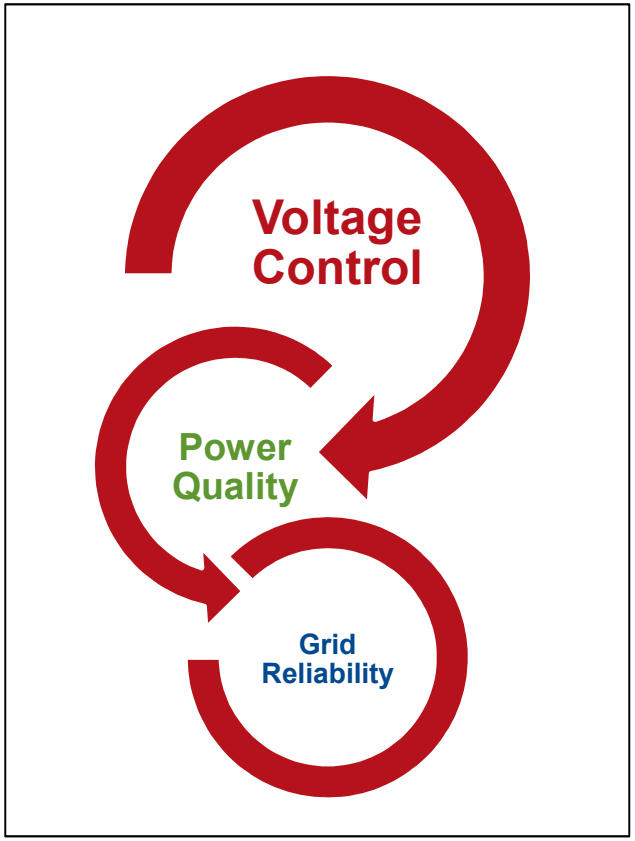
Essex STATCOM Refurbishment Project

Transmission System Reliability Support

Critical System Support Functions

*Provides **Voltage Support** to the transmission and sub-transmission network in Northern Vermont.*

- The STATCOM fast response time ensures a fairly constant voltage to the local load during system disturbances improving the ***Power Quality*** in the local area.
- Avoids voltage collapse under certain system contingency by providing the needed ***dynamic voltage support***.
- The STATCOM also ensures ***Continuous Voltage Controls*** using both the dynamic capabilities from the STATCOM and by controlling the 6 fixed shunt capacitor banks located at Essex (control of 150MVAR of the fixed reactive compensation)



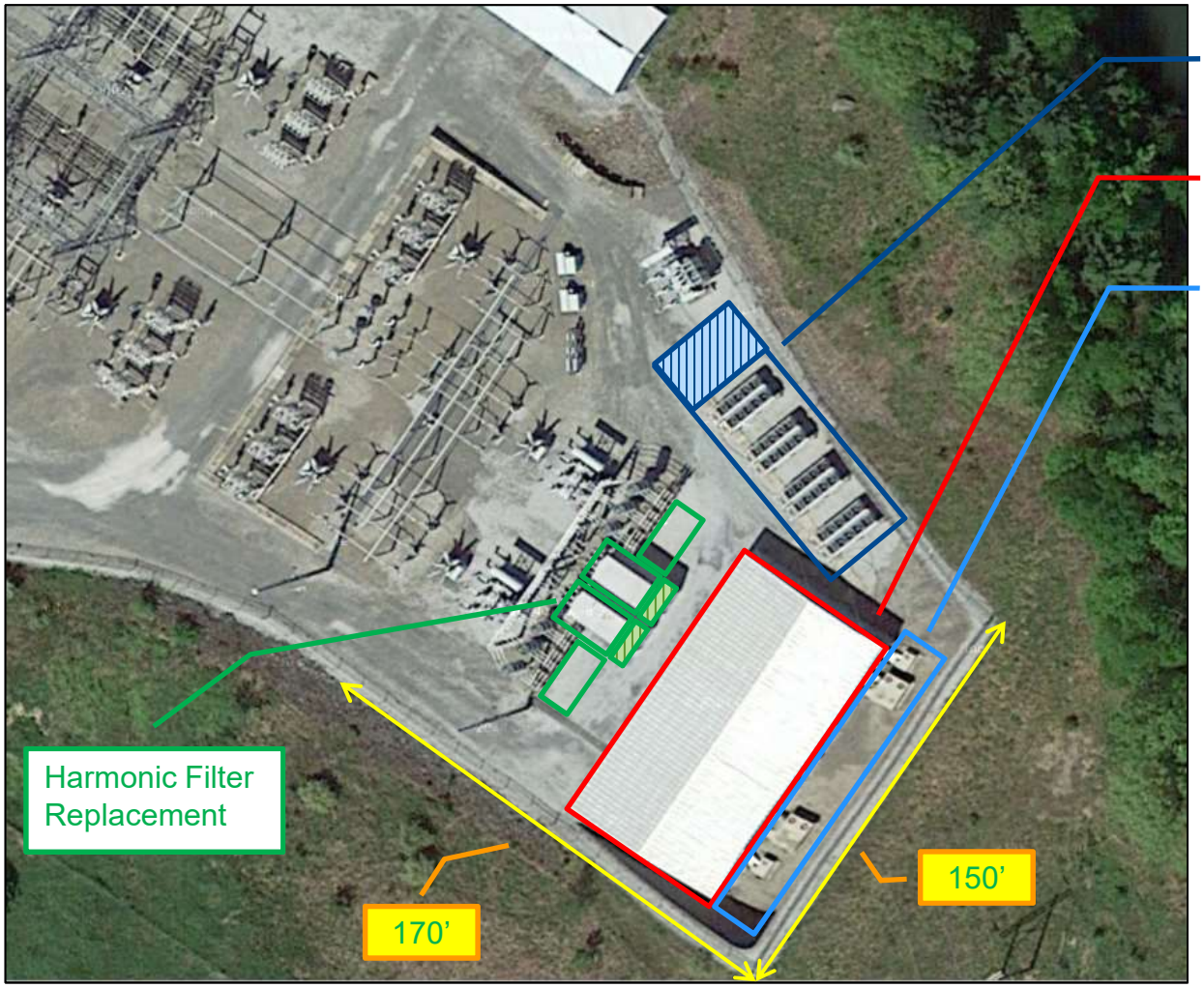
Essex STATCOM Critical Core Functions

PROJECT OVERVIEW

Essex STATCOM Site

Essex STATCOM Scope Overview

Site Overview



Worksite Highlights

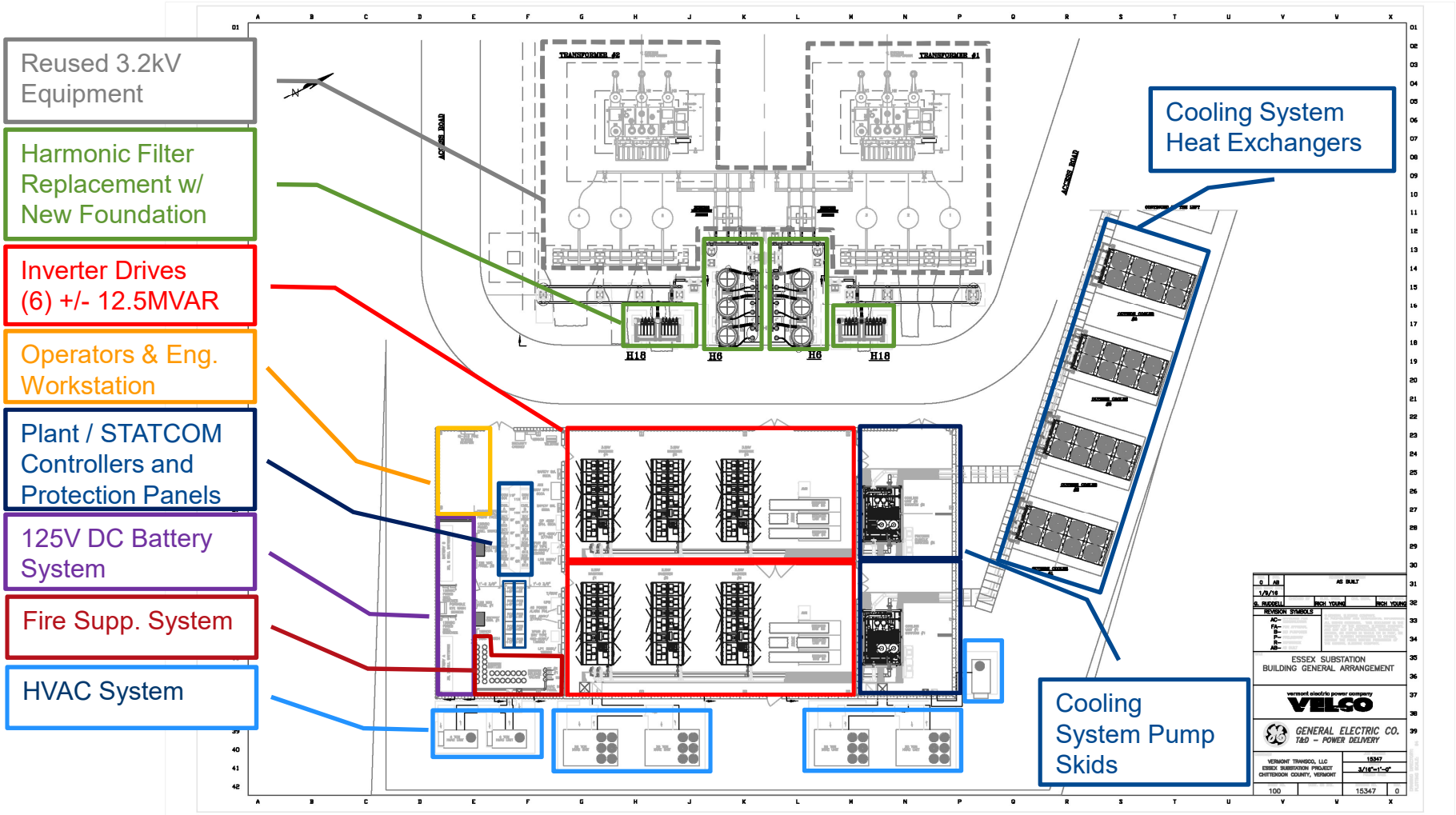
- Very condensed footprint (<0.6 acre)
- Reused major equipment
  - 115/3.2kV Transformers
  - 115kV Breakers
  - 115kV Buswork
  - 3.2kV Buswork
  - STATCOM Building
  - Cooling towers foundations
- Eliminated need for noise enclosure

Essex STATCOM Scope Overview

General Scope Overview

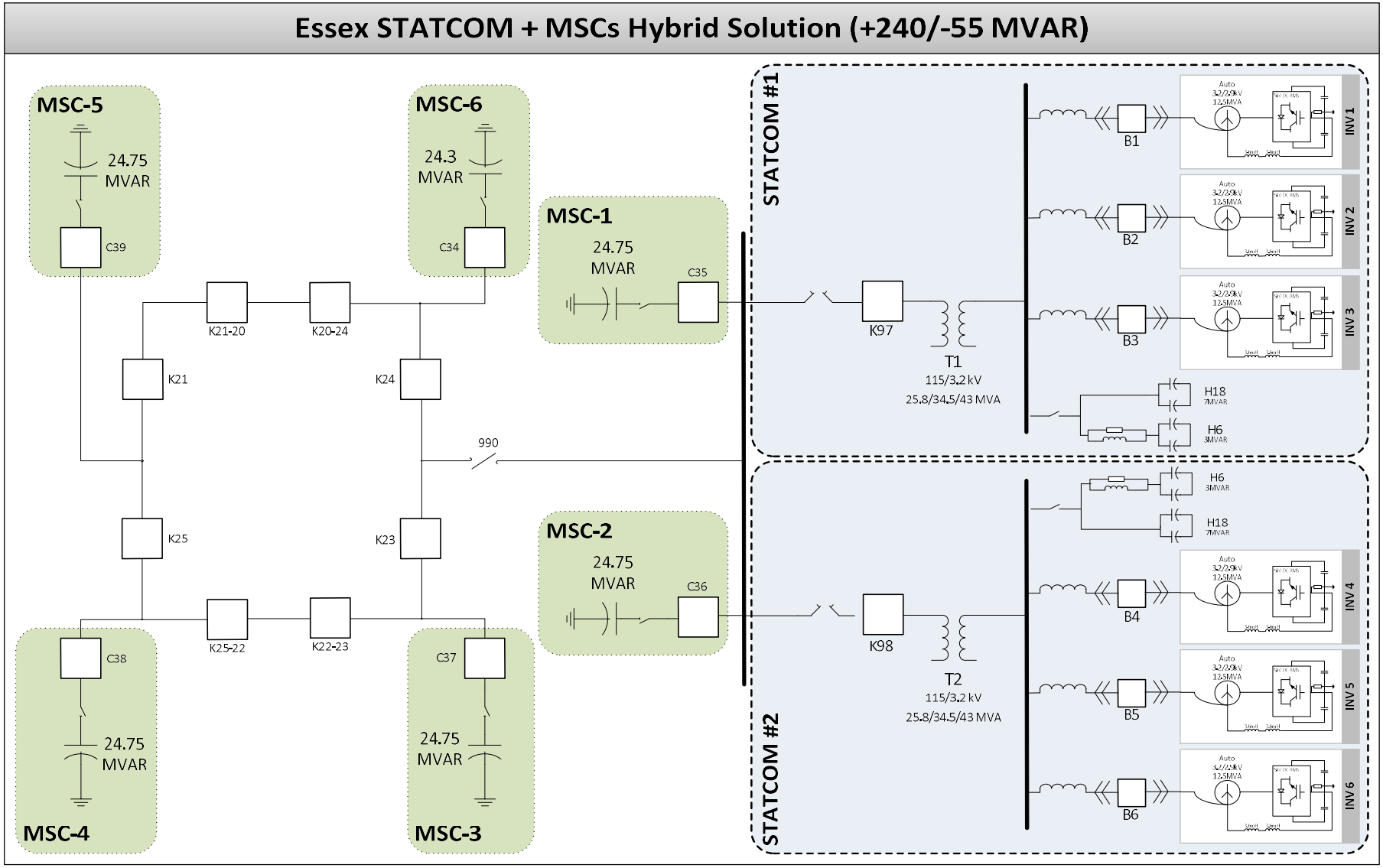
Major equipment change out based on the preferred solution is represented below.

The transformers, main foundations and building remained as well as the 3.2kV bus equipment



Essex STATCOM Scope Overview

STATCOM Configuration

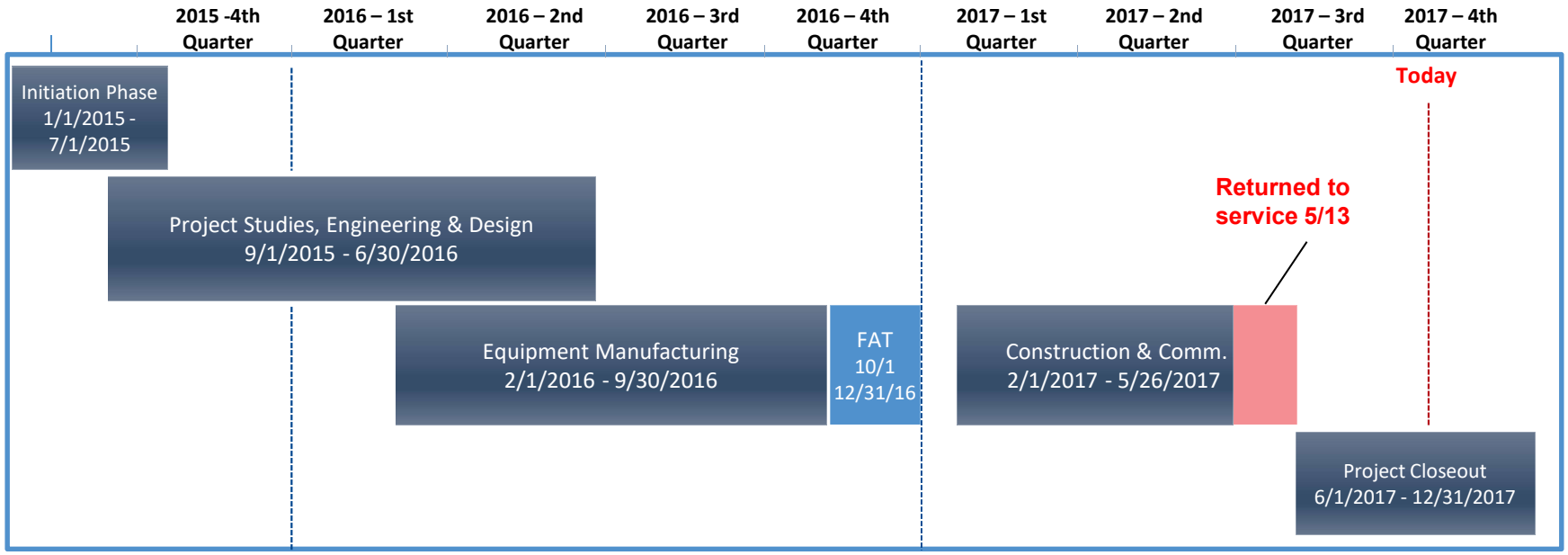


Due to harmonic limitations, the original STATCOM rating was +133/-41 MVAR

Essex STATCOM Scope Overview

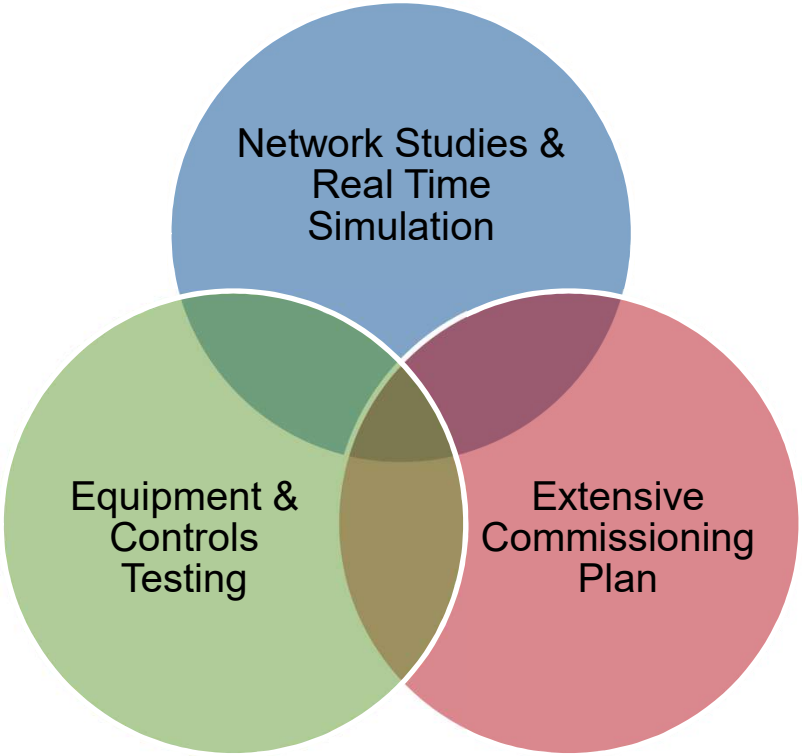
Schedule of Execution

Project closely adhered to the schedule set in 2015. Outage of the existing facility was scheduled 2 years.



Overall Schedule Performance Highlights

- 6 months alternative analysis / RFI Process during initiation phase
- Fast track project from the design phase to commissioning
- Completed construction and commissioning in 7 weeks and 6 days – over 35,000 manhours
- Hourly schedule management during the testing and commissioning phase with close coordination with the grid operators



SYSTEM STUDIES AND EQUIPMENT PERFORMANCE

Performance Studies & Equipment Testing

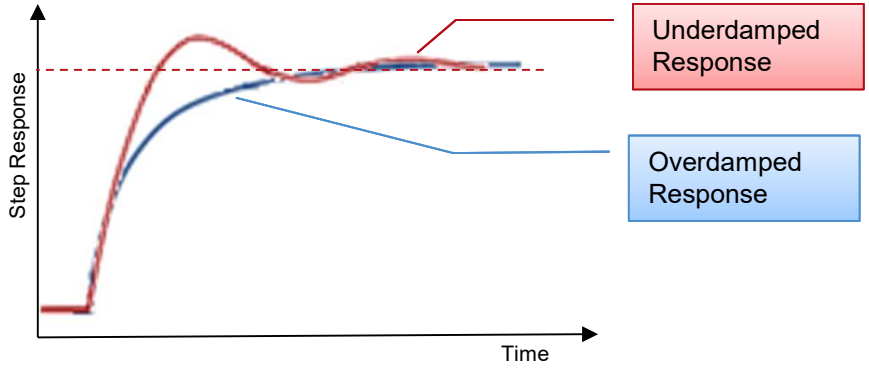
Network and Facility Studies

Controls System Architecture and Redundancy

- STATCOM Controls Fully Redundant / Utility Scale Plant Controller (Mark VIe)
- Degraded Mode Ops (with any combination of 1, 2, 3, 4, 5 or 6 inverters)
- Designed to achieve a high ***Availability and Reliability*** targets of **99.4%**
- Extremely fast controls communication protocols (µs range)

Detail Facility Models and Extensive Performance Studies

- Multiple computer models developed under PSS/e , PSLF and PSCAD – Ensuring accuracy of the modeling and equipment targeted performance
- PSCAD model includes unique controls features & equipment capabilities which allow for very accurate representation of the STATCOM dynamic performance
- Conducted extended network equivalent to conduct studies in PSS/e , PSLF and PSCAD and validate the models accuracy
- Performance was reviewed in details in PSCAD with extreme fault case simulations, including 3-Phase fault at the primary bus where the STATCOM connects to.



(*) The response time is the elapsed time required for the STATCOM device output to reach 90% of its final value following a step input of sufficient size to cause the STATCOM device output to change from maximum MVAR absorption to maximum MVAR production (or reverse)

Performance Requirements

The following provide some performance criteria under normal voltage control condition (non fault)

- Response time* (AVR) – 50ms
- Maximum overshoot – 10%
- Max Settling time (5%) – 200ms
- Max Settling time (1%) – 500ms

Performance Studies & Equipment Testing

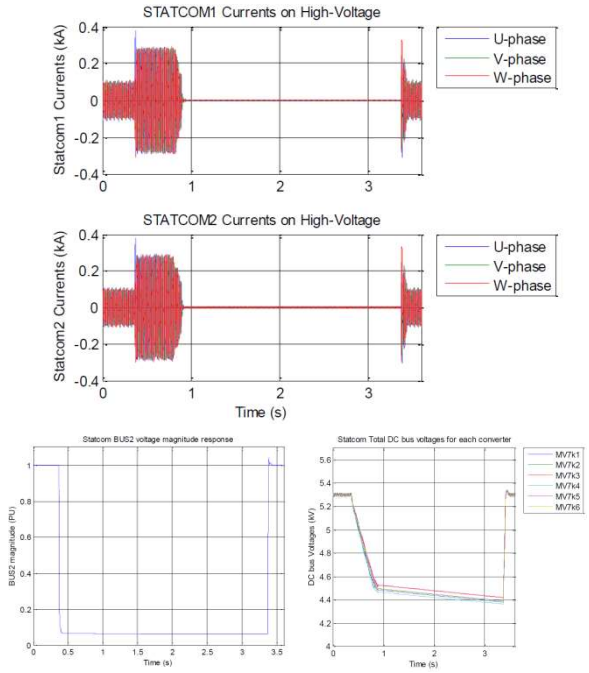
Real Time Digital Simulation (RTDS)

RTDS Simulation with 3-Bus System

- Reflects the actual control system (Hardware in the Loop – HWL)
- Simplified network equivalent system
- Over 30 cases tested

RTDS Simulation with Extended System Modeled

- A larger equivalent system model was developed to simulate system contingencies more representative of the actual network
- Over 20 cases were simulated
- Very complex and elaborate model
- Simulation of degraded mode or system contingencies



RTDS Key findings

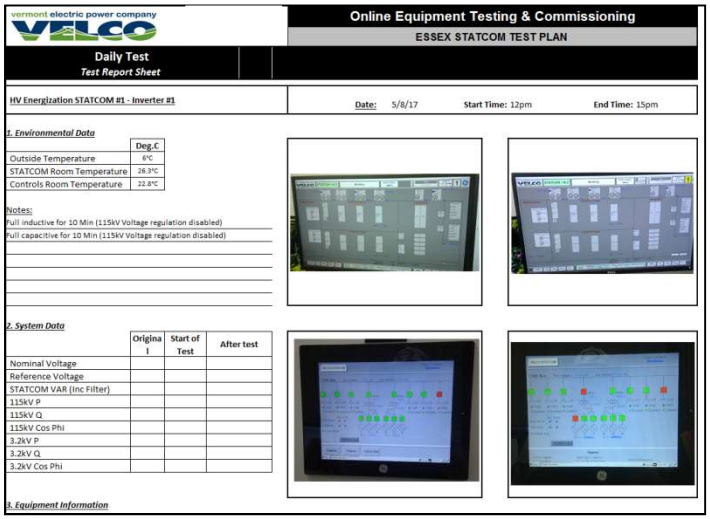
- Very fast STATCOM response: 35ms – 40ms
- Overshoot <3% and Fast settling time
- Identified additional controls optimization *(DC Current and Voltage controls)*

Performance Studies & Equipment Testing

Extensive Commissioning Plan

Testing & Commissioning – Equipment, Controls and Protection Validation

- Extensive equipment and Controls test plan
- 4-weeks of testing (out of 8 weeks outage)
- Equipment performance validation
- Controls and protections testing
- System harmonic performance, voltage controls and power quality management validation
- Hour by hour network testing schedule w/ system risk management and mitigation planning



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Online Equipment Testing & Commissioning

ESSEX STATCOM TEST PLAN

Daily Test

Test Report Sheet

HV Energization STATCOM #1 - Inverter #1 | Date: 5/8/17 | Start Time: 12pm | End Time: 15pm

1. Environmental Data

	Deg.C
Outside Temperature	6°C
STATCOM Room Temperature	26.3°C
Controls Room Temperature	22.8°C

Notes:
Full inductive for 10 Min (115kV Voltage regulation disabled)
Full capacitive for 10 Min (115kV Voltage regulation disabled)

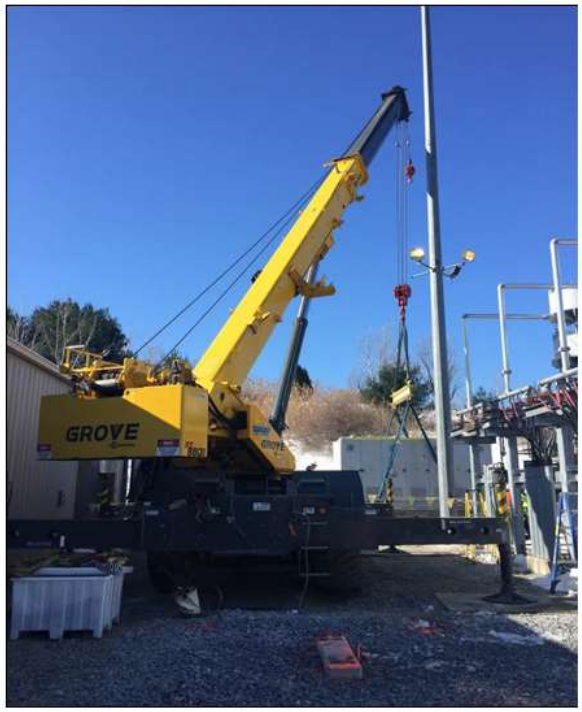
2. System Data

	Original	Start of Test	After test
Nominal Voltage			
Reference Voltage			
STATCOM VAR (Inc Filter)			
115kV P			
115kV Q			
115kV Cos Phi			
3.2kV P			
3.2kV Q			
3.2kV Cos Phi			

3. Equipment Information

						Operation's DATA ONLY								
Day / Time	Test Descriptions	Inductive / Capacitive (System)	STATCOM 1 & 2 Reactive Power (MVAR)	Filter Banks (MVAR)	Fixed Capacitor Bank Switching (MVAR)	Total Reactive System Impact (MVAR)	Trans. Element Ops (Y/N)	Estimated Voltage Impact (KV)	Estimated Voltage Rise (%)	Voltage Steady State (kV)	Bus Voltage if STATCOM trips (% of Voltage	Bus Voltage if STATCOM trips (KV)	Controls (Local / SCADA)	Test Sheet	Note - Procedure Reference Document / Chapter
Day 10	Wednesday, May 10, 2017	10 - High Power Testing													
9:30	**10.1 HV Energization STATCOM #2 - Inverter #4**														*80% Test (Degraded Mode START Sequence)*
9:30	10.1.1 480V Pre-Charge / Analog input check / Synchrocheck Check	N/A	0.0	0.0	0.0	0.0	N	0.00	0.0%	115.0	0.0%	115.0	Local	LP-S2-INV4-2	Energization Only
9:30	10.1.2 Ready for Operation (RFO) Check	N/A	0.0	0.0	0.0	0.0	N	0.00	0.0%	115.0	0.0%	115.0	Local	LP-S2-INV4-2	Energization Only
9:45	10.1.3 Inverter #4 Heat Run Test Inductive	Inductive	-12.5	10.0	0.0	-2.5	N	-0.14	-0.1%	114.9	0.1%	115.0	Local	LP-S2-INV4-2	Low Power Test - Degraded Mode Start Sequence
10:00	10.1.4 Inverter #4 Heat Run Test Capacitive	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S2-INV4-2	Low Power Test - Degraded Mode Start Sequence
10:00	10.1.5 THM verification	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S2-INV4-2	Low Power Test - Degraded Mode Start Sequence
10:00	10.1.6 Bus Differential Testing	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S2-INV4-2	Low Power Test - Degraded Mode Start Sequence
10:30	**10.2 HV Energization STATCOM #1 - Inverter #2**														*80% Test (Degraded Mode START Sequence)*
10:45	10.2.1 480V Pre-Charge / Analog input check / Synchrocheck Check	N/A	0.0	0.0	0.0	0.0	N	0.00	0.0%	115.0	0.0%	115.0	Local	LP-S1-INV2-2	Energization Only
10:45	10.2.2 Ready for Operation (RFO) Check	N/A	0.0	0.0	0.0	0.0	N	0.00	0.0%	115.0	0.0%	115.0	Local	LP-S1-INV2-2	Energization Only
11:00	10.2.3 Inverter #2 Heat Run Test Inductive	Inductive	-12.5	10.0	0.0	-2.5	N	-0.14	-0.1%	114.9	0.1%	115.0	Local	LP-S1-INV2-2	Low Power Test - Degraded Mode Start Sequence
11:15	10.2.4 Inverter #2 Heat Run Test Capacitive	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S1-INV2-2	Low Power Test - Degraded Mode Start Sequence
11:15	10.2.5 THM verification	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S1-INV2-2	Low Power Test - Degraded Mode Start Sequence
11:15	10.2.6 Bus Differential Testing	Capacitive	12.5	10.0	0.0	22.5	N	1.29	1.1%	116.3	-1.1%	115.0	Local	LP-S1-INV2-2	Low Power Test - Degraded Mode Start Sequence
14:00	**10.3 STATCOM #2 High Power Test**														
14:00	10.3.1 Maximum Inductive Power Test	Inductive	-37.5	10.0	25.0	-2.5	Y	-0.14	-0.1%	114.9	1.4%	116.4	Local	HR-S2-INV456 - Max	High Power Test - One 25MVAR Cap Bank
14:00	10.3.2 Cooling System Performance Verifications	Inductive	-37.5	10.0	25.0	-2.5	Y	-0.14	-0.1%	114.9	1.4%	116.4	Local	HR-S2-INV456 - Max	High Power Test - One 25MVAR Cap Bank
14:00	10.3.3 THM verification	Inductive	-37.5	10.0	25.0	-2.5	Y	-0.14	-0.1%	114.9	1.4%	116.4	Local	HR-S2-INV456 - Max	High Power Test - One 25MVAR Cap Bank
14:00	10.3.4 Harmonic Measurement	Inductive	-37.5	10.0	25.0	-2.5	Y	-0.14	-0.1%	114.9	1.4%	116.4	Local	HR-S2-INV456 - Max	High Power Test - One 25MVAR Cap Bank

CONSTRUCTION HIGHLIGHTS



Lifting Inverters into the building (26,000 lbs each)

Construction Highlights
STATCOM Inverters

Each STATCOM includes (3) 12.5 MVAR Inverters for a total of 6 drives

- Each drive weights 26,000 lbs. Complex lifting and rigging work plan was developed to bring the equipment to position
- New cooling system piping to each inverters and bypass arrangement for individual drive maintenance while maintaining the rest of the facility in service
- Modular power stack leveraging IEGT press pack technology
- Designed to sustain long fault duration (DC Capacitors / IEGT)
- All equipment enclosures are arc flash resistant to allow access and individual inverter maintenance

STATCOM #1 – Inverters and 3.2kv Switchgear

Construction Highlights
Harmonic Filters

Harmonics Filter Banks

- (2) 6th Rank Harmonic Filter and (2) 18th Rank Harmonic Filter Banks to improve the facility harmonic performance
- Complex civil construction due to limited space
- Compact design with low noise equipment alleviating the need for noise enclosure improving equipment maintainability
- TIF_{MAX} = 6 (limit = 20) with all inverters in service (studies included all harmonics up to H_{100}). Harmonic performance validated during commissioning

STATCOM Harmonic Filters Arrangement

Construction Highlights
Air Heat Exchangers

4 Heat Exchangers / 8 Cooling coils

- 4 High Efficiency V-Shape Heat Exchangers
- Low noise level / Energy Efficient EC fans with over duty capability
- Conversion to Propylene Glycol (vs. Ethylene Glycol before) which is more environmentally friendly
- Tight work area with overhead 115kV energized line

Cooling System – Outdoor Hear Exchangers

Construction Highlights

Cooling Room Equipment

Independent Cooling Skid for each STATCOM with critical components redundancy including:

- Pump redundancy on each cooling skid
- Redundancy sensors for ease of maintenance and increased reliability
- All new piping and cooling equipment except for the piping to the outdoor heat exchangers

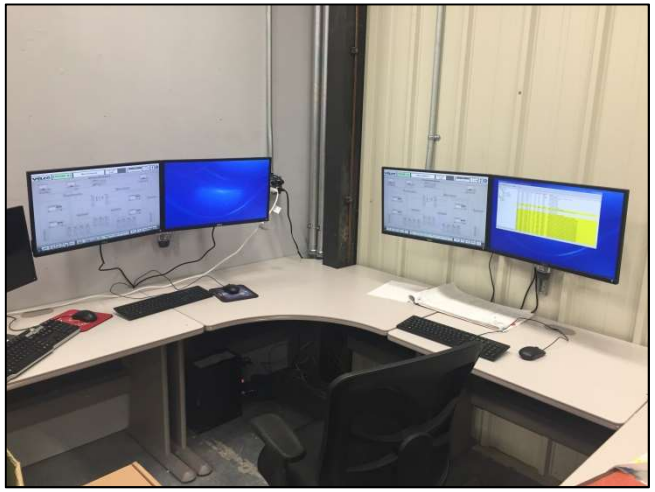
STATCOM #1 – Cooling Skid & Hoist Mechanism for Maintenance

Construction Highlights

Plant and STATCOMs Control System

Fully redundant control system

- Each STATCOM is piloted by its own controls but all the drive are operated in close coordination
- Each STATCOM controls can take over the operation of all the drives without interruption
- STATCOM can operate with 6, 5, 4, 3, 2 or 1 drive only
- New redundant protection equipment



Animated Content

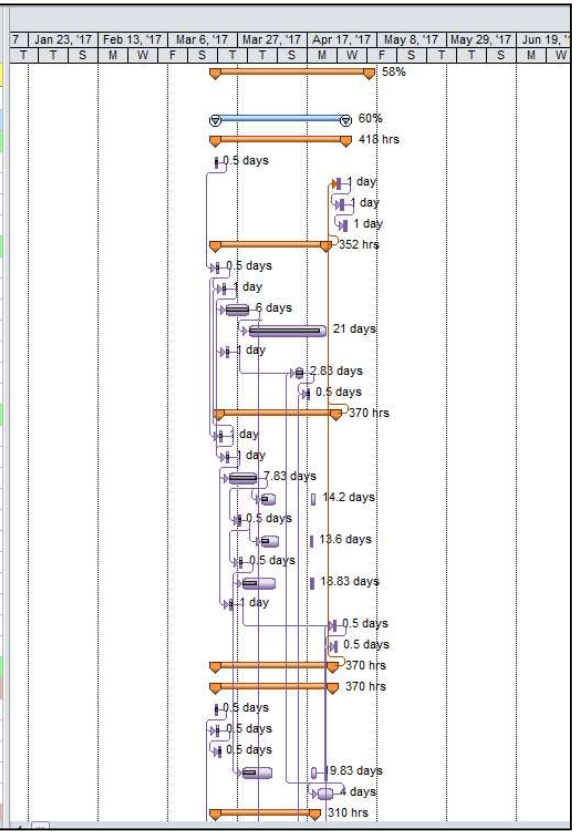
Construction Highlights

Schedule Performance

Construction management highlights

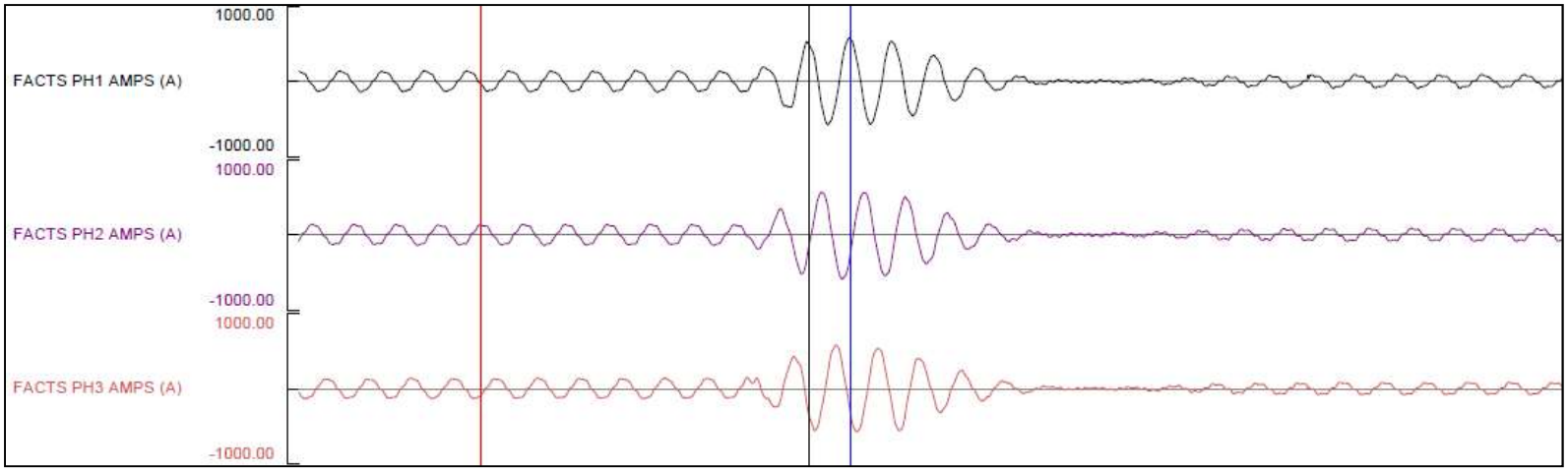
- 8 weeks outage window – 4 weeks for construction and 4 weeks of testing & commissioning
- Daily schedule monitoring and progressing – On-track and off-track activity monitoring
- Hourly testing and commissioning schedule & planning
- Construction completed 4 days ahead of schedule providing additional time for testing & commissioning
  7 weeks and 6 days total outage duration

	'orma dicati	Task Name	Duration	% Comp.	Start	Finish	Project Start Baseline	Project Finish Baseline	Actual Start
1		**1 Construction**	**490 hrs**	**58%**	**Mon 3/20/17**	**Fri 5/5/17**	**Mon 3/20/17**	**Tue 5/9/17**	**Mon 3/20/17**
2	✓	1.1 Outage Starts	0 hrs	100%	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17
3		**1.2 Control & Protection Equipment**	418 hrs	60%	Mon 3/20/17	Fri 4/28/17	**Mon 3/20/17**	**Mon 5/1/17**	**Mon 3/20/17**
4		**1.2.1 Installation of OWS**	**418 hrs**	**14%**	**Mon 3/20/17**	**Fri 4/28/17**	**Mon 3/20/17**	**Fri 4/21/17**	**Mon 3/20/17**
5	✓	1.2.1.1 Remove old Control Equipment	0.5 days	100%	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17
6		1.2.1.2 Install Table and OWS	1 day	0%	Wed 4/26/17	Wed 4/26/17	Tue 4/18/17	Wed 4/19/17	NA
7		1.2.1.3 Install Desk and Position WS	1 day	0%	Thu 4/27/17	Thu 4/27/17	Wed 4/19/17	Thu 4/20/17	NA
8		1.2.1.4 Testing of OWS	1 day	0%	Fri 4/28/17	Fri 4/28/17	Thu 4/20/17	Fri 4/21/17	NA
9		**1.2.2 PCA & PCB - STATCOM Control Installation**	**352 hrs**	**94%**	**Mon 3/20/17**	**Sat 4/22/17**	**Mon 3/20/17**	**Thu 4/13/17**	**Mon 3/20/17**
10	✓	1.2.2.1 Remove old Controls Cubicles	0.5 days	100%	Mon 3/20/17	Tue 3/21/17	Mon 3/20/17	Tue 3/21/17	Mon 3/20/17
11	✓	1.2.2.2 Install PCA and PCB	1 day	100%	Wed 3/22/17	Thu 3/23/17	Wed 3/22/17	Thu 3/23/17	Wed 3/22/17
12	◆	1.2.2.3 Controls Wiring in PCA and PCB	6 days	100%	Thu 3/23/17	Thu 3/30/17	Thu 3/23/17	Mon 3/27/17	Thu 3/23/17
13		1.2.2.4 Controls Terminations in PCA and PCB	21 days	90%	Thu 3/30/17	Sat 4/22/17	Thu 3/23/17	Thu 4/13/17	Thu 3/30/17
14	✓	1.2.2.5 125 VDC Wiring	1 day	100%	Thu 3/23/17	Fri 3/24/17	Thu 3/23/17	Fri 3/24/17	Thu 3/23/17
15	◆	1.2.2.6 125 VDC Termination	2.83 days	100%	Thu 4/13/17	Sat 4/15/17	Fri 3/24/17	Fri 3/24/17	Thu 4/13/17
16	◆	1.2.2.7 125 VDC Energization	0.5 days	100%	Mon 4/17/17	Mon 4/17/17	Tue 3/28/17	Tue 3/28/17	Mon 4/17/17
17		**1.2.3 Protection and Controls Cubicles**	**370 hrs**	**52%**	**Tue 3/21/17**	**Tue 4/25/17**	**Tue 3/21/17**	**Tue 4/18/17**	**Tue 3/21/17**
18	✓	1.2.3.1 Remove old Controls Cubicles	1 day	100%	Tue 3/21/17	Wed 3/22/17	Tue 3/21/17	Wed 3/22/17	Tue 3/21/17
19	✓	1.2.3.2 Install Duplex Tunnel Cubicles	1 day	100%	Thu 3/23/17	Fri 3/24/17	Thu 3/23/17	Fri 3/24/17	Thu 3/23/17
20	◆	1.2.3.3 Controls Wiring in P&C Cubicles	7.83 days	100%	Fri 3/24/17	Sat 4/1/17	Fri 3/24/17	Mon 3/27/17	Fri 3/24/17
21		1.2.3.4 Controls Termination in P&C Cubicles	14.2 days	34%	Mon 4/3/17	Wed 4/19/17	Mon 3/27/17	Tue 4/4/17	Mon 4/3/17
22	✓	1.2.3.5 DFR Wiring in P&C Cubicles	0.5 days	100%	Mon 3/27/17	Mon 3/27/17	Mon 3/27/17	Mon 3/27/17	Mon 3/27/17
23		1.2.3.6 DFR Termination in P&C Cubicles	13.6 days	40%	Mon 4/3/17	Tue 4/18/17	Mon 3/27/17	Sat 4/8/17	Mon 4/3/17
24	✓	1.2.3.7 Protection Wiring in P&C Cubicles	0.5 days	100%	Mon 3/27/17	Tue 3/28/17	Mon 3/27/17	Tue 3/28/17	Mon 3/27/17
25		1.2.3.8 Protection Termination in P&C Cubicles	18.83 days	48%	Tue 3/28/17	Tue 4/18/17	Tue 3/28/17	Tue 4/11/17	Tue 3/28/17
26	✓	1.2.3.9 125 VDC Wiring	1 day	100%	Fri 3/24/17	Sat 3/25/17	Fri 3/24/17	Sat 3/25/17	Fri 3/24/17
27		1.2.3.10 125 VDC Termination	0.5 days	0%	Tue 4/25/17	Tue 4/25/17	Mon 4/17/17	Mon 4/17/17	NA
28		1.2.3.11 125 VDC Energization	0.5 days	0%	Tue 4/25/17	Tue 4/25/17	Mon 4/17/17	Tue 4/18/17	NA
29		**1.2.4 Power Supply**	**370 hrs**	**55%**	**Mon 3/20/17**	**Mon 4/24/17**	**Mon 3/20/17**	**Mon 4/17/17**	**Mon 3/20/17**
30		**1.2.4.1 Building and Auxiliary Station Service**	**370 hrs**	**38%**	**Mon 3/20/17**	**Mon 4/24/17**	**Mon 3/20/17**	**Mon 4/17/17**	**Mon 3/20/17**
31	✓	1.2.4.1.1 Remove Old Equipment	0.5 days	100%	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17	Mon 3/20/17
32	✓	1.2.4.1.2 Install New Rack, Switches, Cables and Trf Diff.	0.5 days	100%	Mon 3/20/17	Tue 3/21/17	Mon 3/20/17	Tue 3/21/17	Mon 3/20/17
33	✓	1.2.4.1.3 Testing & Commissioning LP & DP Panels	0.5 days	100%	Tue 3/21/17	Tue 3/21/17	Tue 3/21/17	Tue 3/21/17	Tue 3/21/17
34		1.2.4.1.4 120 VAC Wiring	19.83 days	40%	Tue 3/28/17	Wed 4/19/17	Tue 3/28/17	Fri 3/31/17	Tue 3/28/17
35		1.2.4.1.5 120 VAC Terminations	4 days	0%	Thu 4/20/17	Mon 4/24/17	Sat 4/15/17	Mon 4/17/17	NA
36		**1.2.4.2 480V Power Supply**	**310 hrs**	**60%**	**Mon 3/20/17**	**Wed 4/19/17**	**Mon 3/20/17**	**Sat 4/1/17**	**Mon 3/20/17**



Daily Schedule Performance Monitoring and Control

RECENT SYSTEM EVENTS



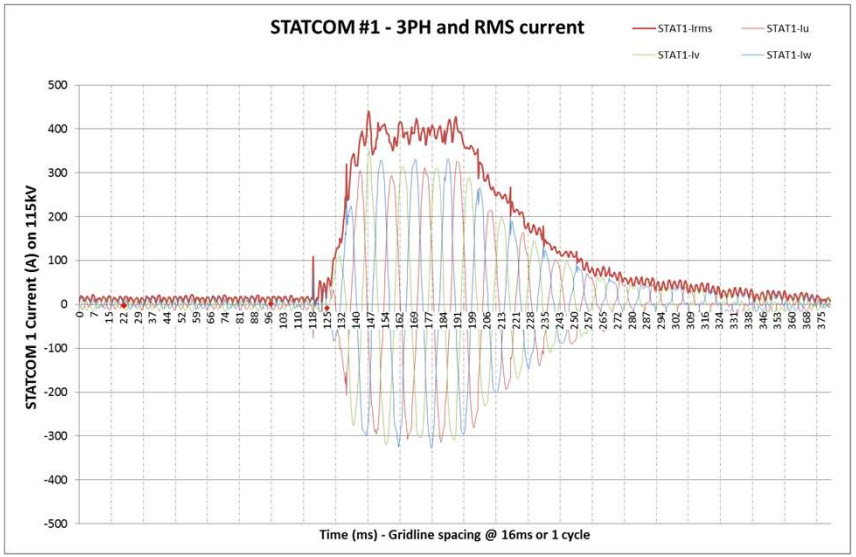
STATCOM Current Sine wave during a recent system event and as recorded by the Essex STATION DFR

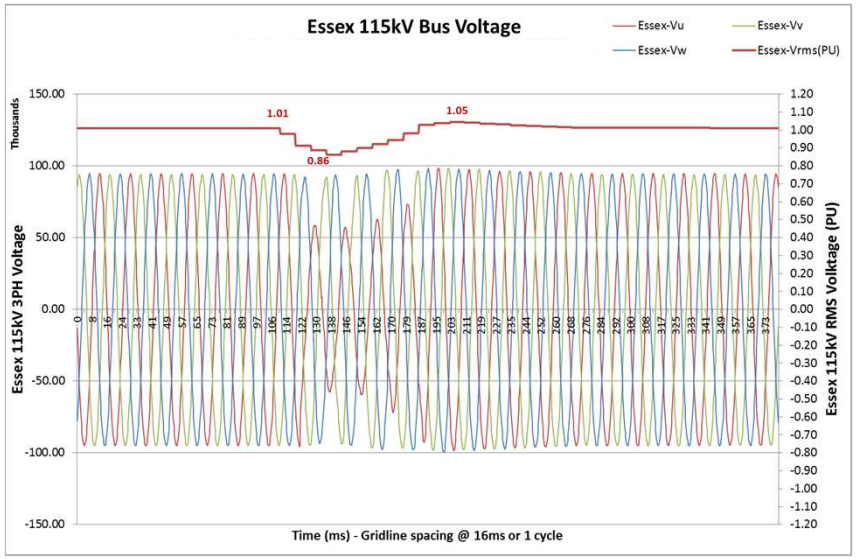
Essex STATCOM Response to Recent System Events

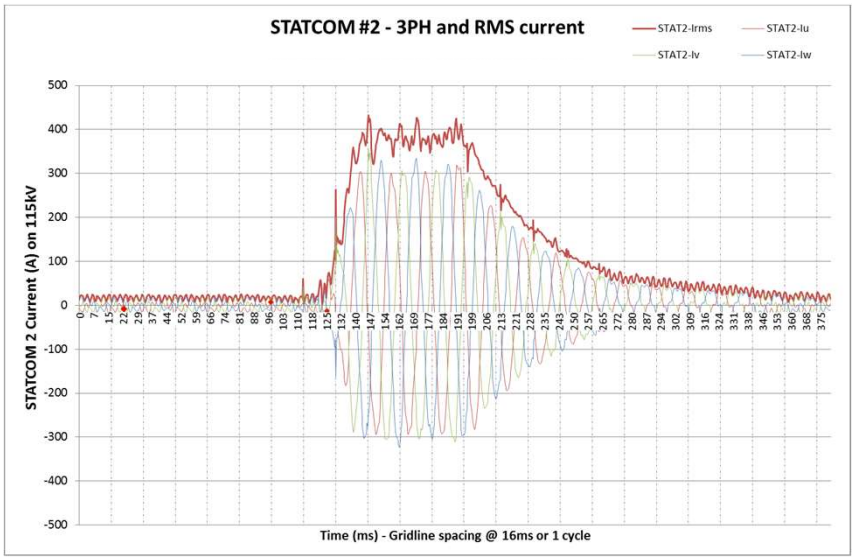
STATCOM Performance Review

34.5kV Fault at Essex

- Essex STATCOM bus voltage and very smooth voltage sine wave. Minimum harmonics observed
- Review the network and STATCOM response and stability (~3% overshoot / No oscillation on recovery)
- STATCOM 1 and STATCOM 2 response with maximum current output in **1-2 cycles**
- Balanced reactive output between the 2 STATCOMs







Conclusion

System Studies and RTDS Simulations

- Transmission System studies and RTDS simulations validated the performance of the new STATCOM equipment
- The control system settings were optimized based on the studies and RTDS results

Construction Sequence and Testing and Commissioning Plan

- The project was completed on time and within the outage window established in 2015
- Conducted many high power and low power tests to validate equipment performance
- Network harmonic performance was monitored and found to meet or exceed the results from the design studies

Facility Performance Assessment

- The STATCOM architecture has been optimized to provide high availability and reliability performance
- Fully leverage all the assets available at the Essex Substation (Capacitor banks control) providing a very wide range of operational capabilities at the STATCOM
- The STATCOM's performed well during recent system events

Questions

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