

## Operational Experience of Essex STATCOM after Refurbishment

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### SUMMARY

Vermont Electric Power Company Inc. (VELCO) installed a STATCOM at Essex Substation in 2001 to provide steady state and dynamic system voltage support and to improve power quality in the Chittenden County area in the state of Vermont, USA.

The original Essex STATCOM facility operated without any extended major forced or scheduled outage until it was de-commissioned. However, by 2014 there were significant reliability concerns related to the aging control system hardware and obsolescent software. At the same time, the system reliability and availability requirements associated with significant additions of renewable generation including both wind and solar farms in Vermont were becoming more stringent. Thus, in 2014, VELCO performed a detailed technical assessment to evaluate facility condition and options to extend its useful life and to improve its performance. The recommendation following the assessment was to refurbish the existing facility [1].

The refurbishment project was kicked off in July 2015 and completed in May 2017. The scope of work included upgrades of the inverters, control and protection systems, cooling systems and some of the auxiliary equipment as well as replacement of aging computer hardware and obsolete software in the HMI [2] [3]. The upgraded Essex STATCOM retains the modular design of original STATCOM but with more flexibility on operating STATCOM units and inverter units under various normal and degraded operation modes. In addition to the replacement of obsolete hardware and software, the dynamic range has also been slightly expanded from original output of -41 MVAR (Inductive) and +133 MVAR (Capacitive) to -55 MVAR (Inductive) and +145 MVAR as a result of new harmonic filters at 3.2kV.

This paper presents VELCO's operational experience of the Essex STATCOM including its performance evaluated by the reliability, availability and maintenance data (RAM) of the facility since it was re-commissioned in 2017.

### KEYWORDS

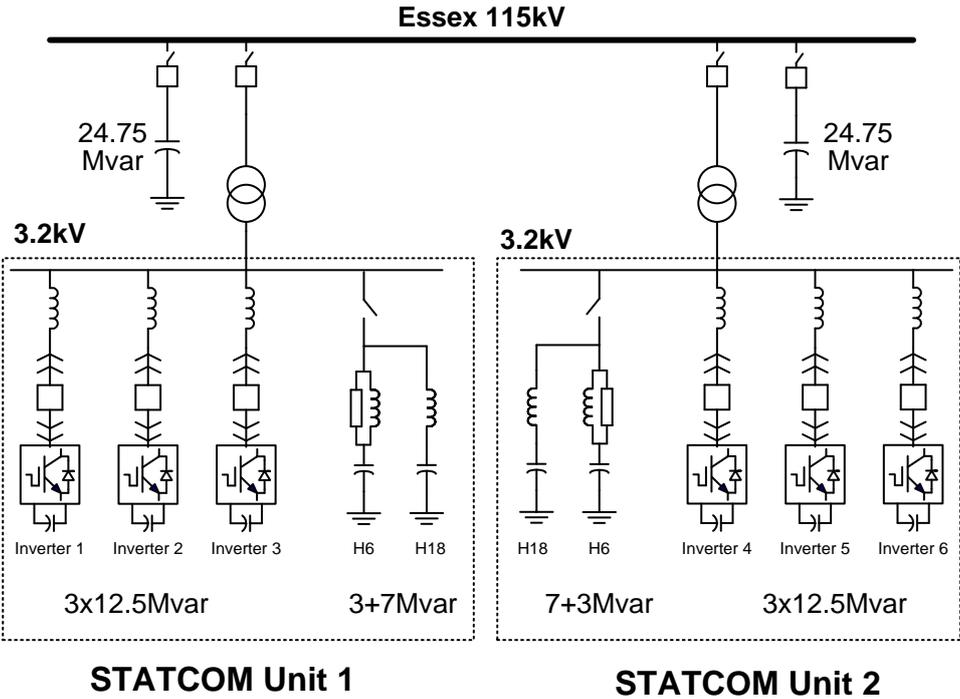
FACTS device, STATCOM, Refurbishment and upgrade, IEGT, 3-level VSC, RAM, Operational performance, Cigre FACTS protocol

**INTRODUCTION**

The STATCOM installed by Vermont Electric Power Company Inc. (VELCO) at Essex Substation in 2001 features a modular design based on voltage sourced converter technology to provide voltage support during both dynamic and steady state conditions as well as power quality improvement in the Chittenden County area in the state of Vermont, USA.

During years 2015 to 2017, this facility was refurbished and upgraded due to the significant concerns of the aging control system hardware and obsolescent software as well as more stringent reliability and availability requirements associated with significant additions of renewable generation including both wind and solar farms in Vermont [1]. The scope of work included upgrades of the inverters, controls and protection system, cooling system and some of the auxiliary equipment as well as replacement of aging computer hardware and obsolete software in the HMI [2] [3].

The upgraded Essex STATCOM retains the modular design of original STATCOM as shown in Figure 1. It offers more flexibility on operating STATCOM units and Inverter units under various normal and degraded operation modes. In addition to the replacement of obsolete hardware and software, the dynamic range has also been slightly expanded from original output of -41 MVAR (Inductive) and +133 MVAR (Capacitive) to -55 MVAR (Inductive) and +145 MVAR as a result of new harmonic filters at 3.2kV.



*Figure 1 - Upgraded Essex 115kV -55/145Mvar STATCOM Schematics*

The refurbished STATCOM was commissioned in May 2017 and resumed to commercial operation after a month-long trial operation period. This paper describes the operational experience and performance of the Essex STATCOM.

**OPERATIONAL PERFORMANCE**

There have been a significant number of incidents and outage events since the re-furbished Essex STATCOM started commercial operation on June 26, 2017. Table 1 summarizes the both forced outage (FOU) and scheduled outage (SOU) events which occurred in both 2017 and 2018. The performance

of facility is being monitored and measured using the Cigre protocol for reporting operational performance of FACTS [4]. The rated capacity for reporting is +75Mvar (Capacitive) and -75Mvar (Inductive) which does not include the reactive power from the ac filters. Although this report discusses the incidents based off of CIGRE reporting, the agreed upon reliability with the Vendor is based on 5 out of 6 Inverters being available. Therefore, the availability numbers may differ slightly when reporting to CIGRE or the Vendor.

Twenty-nine outage events were recorded during the first two years of operation. The actual outage hours (AOD) were recorded for each event and then converted to equivalent outage hours by multiplying AOD with outage derating factor (ODF) which is the ratio of outage capacity (Qo) to rated capacity (Qm). More detailed descriptions of these indices can be found in Appendix Table A-1.

Table 1 – Forced and Scheduled Outage Events List<sup>1</sup>

DATE	Outage Due to	Outage Type	Outage Code	Actual Outage Hours AOD	Equivalent Outage Hours EOD	Outage Derating Factor ODF	Outage Capacity Qo		Restoration Code
							Inductive Ra	Capacitive Ca	
2017-Aug-02	Short Circuit	FOU	H	0.05	0.03	0.5	-37.5	37.5	M
2017-Aug-18	Hotspot on Filter CT	SOU	AC-E.F	2.23	1.12	0.5	-37.5	37.5	R
2017-Oct-17	Hotspot on Resistor	FOU	AC-E.F	14.01	7.01	0.5	-37.5	37.5	R
2017-Oct-18	Annual Maintenance	SOU	PM	0.93	0.47	0.5	-37.5	37.5	M
2017-Oct-18	Annual Maintenance	SOU	PM	36.10	36.10	1.0	0.0	0.0	M
2018-Feb-02	Hotspot on Reactor	FOU	AC-E.F	1.83	0.92	0.5	-37.5	37.5	R
2018-Feb-20	MV Breaker Inspections & Testing	SOU	PM	1.11	0.19	0.2	-62.5	62.5	M
2018-Feb-20	MV Breaker Inspections & Testing	SOU	PM	23.88	3.98	0.2	-62.5	62.5	R
2018-Feb-21	MV Breaker Inspections & Testing	SOU	PM	1.33	0.22	0.2	-62.5	62.5	M
2018-Feb-21	MV Breaker Inspections & Testing	SOU	PM	1.15	0.19	0.2	-62.5	62.5	M
2018-Feb-22	MV Breaker Inspections & Testing	SOU	PM	1.20	0.20	0.2	-62.5	62.5	M
2018-Feb-22	MV Breaker Inspections & Testing	SOU	PM	1.08	0.18	0.2	-62.5	62.5	M
2018-Jun-08	Planned Spring Outage	SOU	PM	0.45	0.23	0.5	-37.5	37.5	M
2018-Jun-08	Planned Spring Outage	SOU	PM	30.58	30.58	1.0	0.0	0.0	M
2018-Sep-04	Control System Watchdog Failure	FOU	CP	23.61	23.61	1.0	0.0	0.0	M
2018-Sep-05	Control System Communications	FOU	CP	4.16	4.16	1.0	0.0	0.0	M
2018-Sep-06	MV Breaker Trip Coil Monitoring	FOU	AC-E.SW	0.16	0.08	0.5	-37.5	37.5	M
2018-Sep-06	MV Breaker Trip Coil Monitoring	FOU	AC-E.SW	2.13	0.36	0.2	-62.5	62.5	R
2018-Nov-29	Fast Stop Testing	SOU	CP	1.53	1.53	1.0	0.0	0.0	M
2018-Nov-29	Fast Stop Testing	SOU	CP	0.53	0.53	1.0	0.0	0.0	M
2018-Nov-30	MV Breaker Trip Coil Monitoring	FOU	AC-E.SW	0.15	0.08	0.5	-37.5	37.5	M
2018-Nov-30	MV Breaker Trip Coil Monitoring	FOU	AC-E.SW	63.45	10.58	0.2	-62.5	62.5	S
2018-Nov-30	Main Computer Crash	FOU	CP	0.20	0.20	1.0	0.0	0.0	M
2018-Dec-19	Remote Monitoring Installation	SOU	CP	2.44	2.44	1.0	0.0	0.0	M
2019-Jan-20	Inverter 6 Trip – LOV Hi Temp	FOU	AC	1.71	0.29	0.2	-62.5	62.5	M
2019-Feb-20	Inverter 6 Repair	SOU	AC.E.SW	1.90	0.32	0.2	-62.5	62.5	M
2019-May-29	Annual Maintenance	SOU	PM	30.83	30.83	1.0	0.0	0.0	M
2019-May-30	MV Breaker Close Coil Failure	FOU	AC-E.SW	10.53	1.76	0.2	-62.5	62.5	M
2019-May-30	Inverter 6 Trip – Failed IEGT	FOU	V	18.05	3.01	0.2	-62.5	62.5	M

Note 1: Refer to Appendix Table A-1 for definition and description of indices used in this table.

The first forced outage was due to a human error where a voltage measurement was attempted using Fluke meter with leads connected for current measurements. The measurement was also taken on the cooling skid which at this point had no redundancy as it was being fed from a single breaker for the control circuit. This tripped the cooling system and consequently STATCOM Unit 2 was tripped

resulting in loss of one-half of the total capacity. The system was restored quickly after the breaker was reset.

Two longer forced outage events were related to hotspots detected on ac equipment. The first hotspot was observed on the resistor of 6<sup>th</sup> harmonic filter for STATCOM Unit 1. The hotspot registered 150C above ambient temperature and could be seen glowing with the naked eye. The STATCOM was shut down immediately without waiting for the scheduled outage. When these resistors were shipped from Europe, four of the seven resistors were damaged. The resistors were rebuilt and tested on site and approved for operation. They were working as expected until Oct 17th, 2017 when the hotspot was noticed. It was confirmed that three resistors that the three resistors that were not damaged had no signs of heating while two of three resistors rebuilt at site showed signs of heating at the same location. Figure 2 shows a close look at the hotspot. The insulator used a non-conductive washer as a spacer between the busbar and the insulator and this washer was completely broken. The busbar itself was bent so much it was not making a solid connection to the thru-rod anymore. The busbar and insulator were replaced for the two resistors that were heated and STATCOM Unit 1 was put back to service.

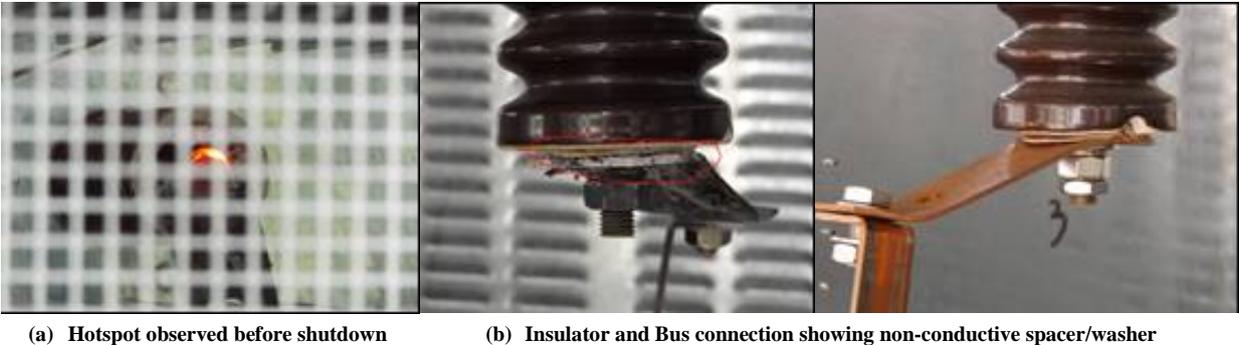


Figure 2 – Hotspot on Filter Resistor

A second hotspot was observed at tap bolt connection on the middle reactor of the 6th Harmonic Filter for STATCOM Unit 2 as shown in Figure 3 (a). The hotspot registered 72C above ambient temperature. STATCOM Unit 2 was shut down immediately. It was confirmed that the hotspot was caused by loose connection as shown in Figure 3 (b) and (c). The connections were cleaned and re-torqued. There have been no signs of a hotspot since STATCOM Unit 2 was restored to service.

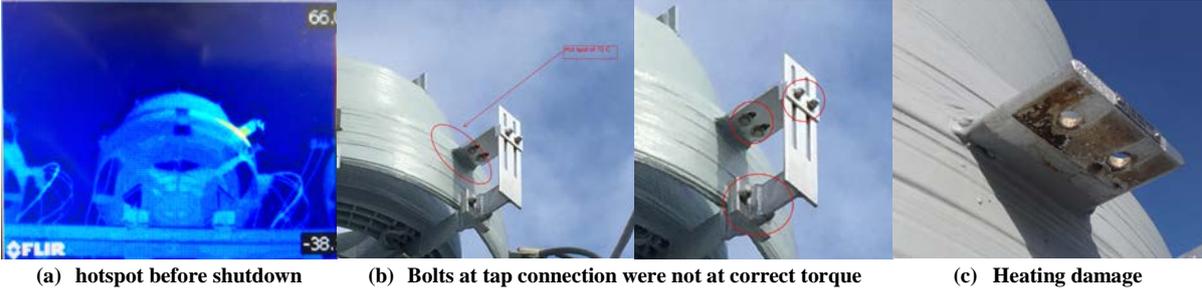


Figure 3 – Hotspot on Filter Reactor Connection

The other three forced outages were related to the control system (PCA/PCB) and interface computers (MKVIe). The first forced outage on Sept 4<sup>th</sup> had a duration of 23.6 hours. This was caused when the health (heartbeat) signal from the MKVIe system that was sent over to the inverter control equipment (PCA/PCB) was lost. The PCA/PCB equipment took the correct action and tried to continue operation of STATCOM 1 using its redundant controls which are located in the PCB controls. However, since PCB also lost its heartbeat signal from MKVIe, PCA/PCB determined that there were no reliable

communications from the MKVIE system and to protect the equipment; a Stop Command was then issued to both STATCOM 1 and STATCOM 2.

In order to reliably protect the inverter equipment; the MKVIE system needs to pass along a healthy signal to PCA/PCB since the trip signals for the high side breakers pass through the MKVIE system. If the tripping path via the MKVIE system is not reliable; the inverter equipment could be vulnerable to damage. Monitoring of the health of the MKVIE was accomplished by using ADD block inside the software. Every time the code is processed (read/computed), the ADD blocks increment and an output is sent to PCA/PCB control system. This worked very well for over a year. However, it was not known that this ADD block had a maximum incremental value. Once this limit was reached, new values ceased to be sent to PCA/PCB. In order to resolve this issue; the ADD block(s) were modified to automatically reset after 1,000,000 scans. With this change, the counters will never reach their maximum value, and heartbeat (life) signals would not cease. It was verified inside the MKVIE equipment that the signal was not lost during the resets.

Another forced outage was caused by a computer crash during the installation of an additional feature to export all log files, event files, and TFR data for analysis and trending so that the cooling system data could be acquired remotely.

Other forced outages were all related to the failures of inverter breaker trip latch. In each case the inverters were started as normal, but once started; a trip coil monitoring alarm would appear. The rack-out breakers at the STATCOM only have one trip coil. Therefore, if the breaker closes and alarms due to trip coil monitoring, the next operation of the breaker would result in a breaker failure condition. In a normal trip coil monitoring circuit, the negative voltage should be pulled through the trip coil and be read on one side of the indicating lights. During these failures, there was no negative voltage which indicated that either the 52a contacts had failed or the trip coil had failed. Since the trip latch was compromised by either the 52a contacts or the trip coil, the decision was made to stop the associated STATCOM, deselect the affected Inverter and restart with a reduced number of inverters. If no action were taken, the next time the affected inverter needed to stop for any reason; it might result in a longer outage since no one would be on site when it occurred. Also, if it were tripped; since it would result in a breaker failure initiation, the entire associated STATCOM unit would trip. Since the breakers rely on a single trip coil, replacement trip coils were ordered and installed for the remaining breakers at the next scheduled outage.

A number of scheduled outages were taken during year 2017 and 2018 to perform annual preventative maintenance, inspect inverter breakers as well as some emergency stop testing. A hotspot (48°C temperature rise) on STATCOM Unit 2 H18 Filter Phase 2 was observed and was fixed. A remote monitoring system was installed at the end of 2018.

There were also some incidents that did not cause forced outages. On Jan 20, 2019 Inverter 6 tripped offline due to excessive neutral reactor temperature, the remaining inverters stayed online. After investigation it was found that there was no software filtering or delays associated with the temperature alarms for the neutral reactors and autotransformers. In this case, a loose wire was found on the neutral reactor which led to an erroneous spike in temperature causing the tripping of Inverter 6. As a result of this, ferrule crimps were added to all temperature wire connections instead of just wires and a software filter was added to provide immunity to short spikes.

On May 30, 2019 when restoring the STATCOM to service after a scheduled outage for annual maintenance, Inverter 5 did not start due to a bad close coil. The inverter was left off for the night, however, in the middle of the night the Highgate Converter was ramped from 20 MW to 219 MW. When the converter output was about 46 MW, the STATCOM reached its inductive limit and shortly thereafter Inverter 6 tripped offline due to a failed IEGT. Upon investigation, the rack out breaker for Inverter 6 was modified and installed in Inverter 5 in order to get Inverter 5 back online. The next day the entire valve stack was replaced for Inverter 6 and the unit was restarted.

## ESSEX STATCOM RAM PERFORMANCE

Figure 4 demonstrates the overall facility performance presented as reliability, availability and maintainability (RAM) since starting commercial operation after the upgrade. The performance is evaluated based on criteria defined in Cigre protocol [4]. Generally, the RAM data is reported based calendar year, thus RAM of 2019 is not covered in this paper.

The total availability of the facility in 2017 was 99.01% and it slightly increased to 99.08% in 2018 as shown in Figure 4 (a). In 2017, the total unavailability was 0.99% and was primarily due to scheduled outage. In 2018, the unavailable caused by both forced and scheduled outages was 0.46% as shown in Figure 4 (b) which resulted in the total unavailability of 0.92%.

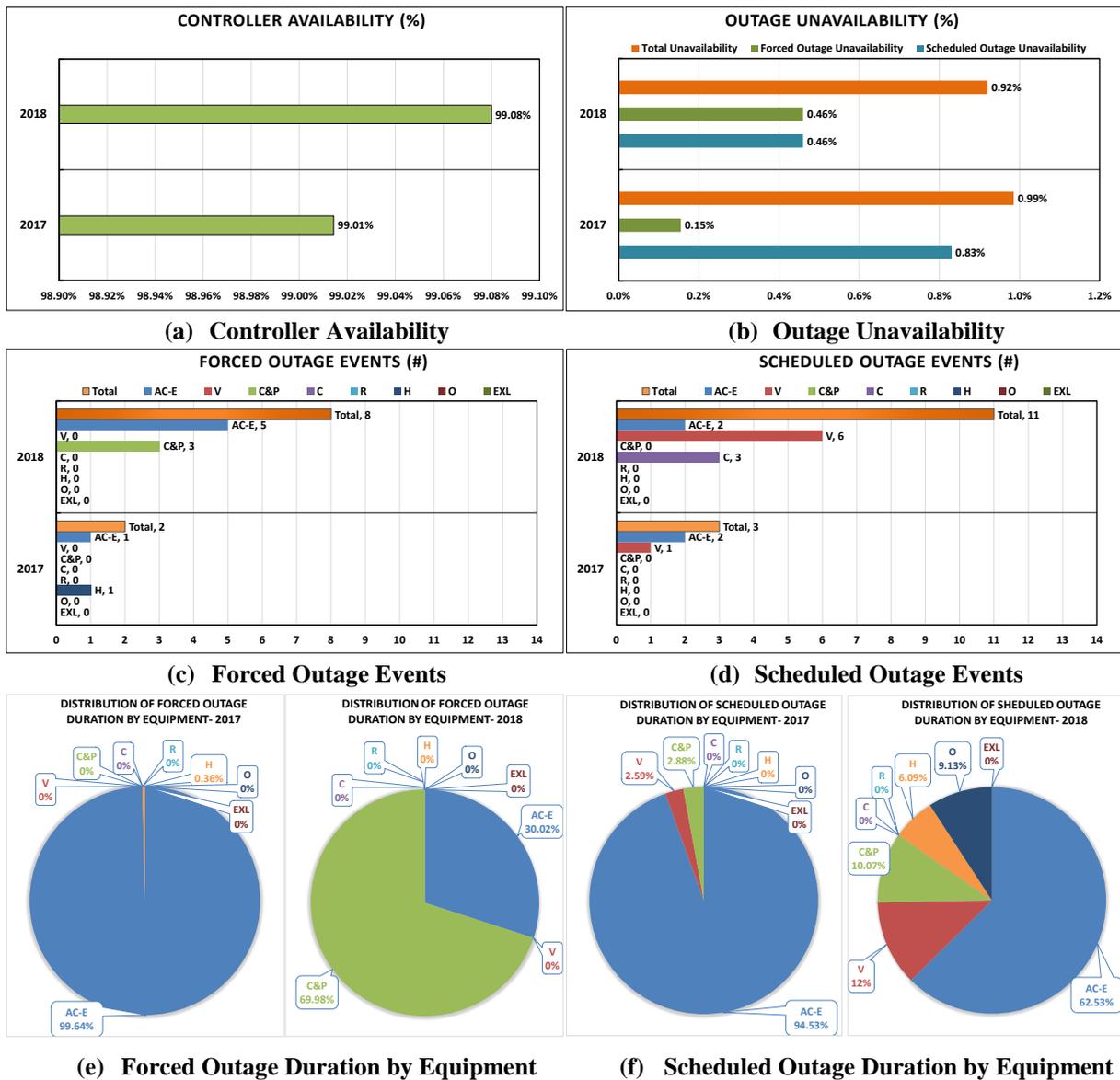


Figure 4 – Essex STATCOM RAM Performance Since the Upgrade

The number of forced and scheduled outage events categorized by STATCOM equipment is presented in Figure 4 (c) and (d). The definition of equipment categories can be found in Appendix Table A-1. Most of forced and scheduled outage events fall into two categories, AC-E (ac equipment) and C&P (control and protection system).

The distribution of outage durations in percentage among all the equipment is presented in Figure 4 (e) and (f). In 2017, 99% of the forced outage time was caused by ac equipment (hotspot issues) and 1% was due to human error. In 2018, 70% of the forced outage time was from C&P system and 30% was due to ac equipment. Most of time, scheduled outages were arranged to fix and inspect ac equipment in both 2017 and 2018. Maintenance of other equipment such as valve and C&P were also performed during scheduled outages in 2018.

## **DISCUSSION**

The overall performance of upgraded STATCOM has been very good as demonstrated by the high availability of more than 99% that has been achieved in each of the two years since refurbishment.

One reason for the high availability is considered to be extensive quality control that was carried out throughout the project by both the technology provider as well as the Owner's management and technical teams. The studies and design were performed with the close involvement and review of the Owner so that the equipment and control features were designed with adequate rating and performance. All the major equipment was factory tested in the presence Owner's team so that the corrections and adjustments could be made at the factory rather than at site. Extensive factory acceptance testing (FAT) of the control systems was performed to prove all functions and performance of the inverter control systems (PCA/PCB). This is considered one of the major successes in the project.

The performance could have been even better except for a number of factors as follows:

a) Failure to include all equipment in the FAT

The FAT testing did not include the HMI MKVIe systems which were developed by a different design team than the inverter controls. Thus, the communications between the MKVIe and the inverter controls could not be tested in the FAT. This subsequently led to a forced outage when the heartbeat signal from the MKVIe to the converter controls ceased. Similarly, the cooling controls which developed by another team were not included in the FAT tests. At site it was discovered that the remote monitoring of the cooling was not possible and the installation of features to allow remote monitoring subsequently resulted in a forced outage. This demonstrates that it is essential to have effective communication between different design groups within the technology supplier's team. It is a common that various parts and systems are provided from different design teams of the supplier. Normally, all subsystems would be tested together at the FAT. However, in this project, this did not occur leading to reduced reliability performance at site.

b) Field repair of shipping damage to filter resistors

The filter resistor was not considered as critical equipment and the Owner's staff did not attend factory testing. Consequently, a design shortcoming of the bushing connections not noticed or corrected in the factory. Further issues occurred when some of the units were damaged during shipment and in the interests of meeting the schedule, a decision to make field repairs was taken. The field repairs were inadequately executed and lead to a forced outage due to hot spots. Further changes to correct a design deficiency of the bushing connections within the resistor housings will be carried out in an upcoming scheduled outage.

c) Inadequate quality control during site installation

Hot spots in the reactor tap connections were found to be the result of failure to adequately torque the bolts on the tap connections. This was not checked by the installer as it was a factory installed connection and was also not caught by the commissioning team. Loose connections were also noted on a CT connection. These issues subsequently led to forced outages.

d) Failure to refurbish some existing equipment that was re-used

The reuse of the existing rack-out switchgear and breakers without replacing the trip coils led to a number of forced outages. Another equipment that was re-used was the series reactors of the inverters. Although the equipment has not failed, audible noise has increased due to differences in harmonic output of the inverters. Further scheduled outages may be needed to install sound shields.

## **CONCLUSIONS**

Although very good reliability performance has been achieved at the Essex STATCOM since refurbishment a number of forced outages have occurred. Most of issues that caused the forced outages addressed in this paper could have been eliminated or minimized by:

- insisting that all control equipment be included the FAT so that all inter-system communications can be tested.
- better quality control of site installation especially torqueing of bolted connections including checking the tightness of factory-made connections.
- refurbishment of re-used equipment especially breakers.
- avoiding field repair of equipment damaged during shipment or better supervision of such repairs.

## **BIBLIOGRAPHY**

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## APPENDIX

Table A-1 – Definitions of Indices used for STATCOM Performance

Index	Abbr.	Definitions
Rated Capacity	Qm	Maximum capacity (+/-MVARs), excluding the added capacity available through means of redundant equipment, for which continuous operation under normal conditions is possible is referred to as the rated capacity.
Outage Capacity	Qo	The capacity reduction (+/-MVARs) which the outage would have caused if the system were operating at its rated capacity (Qm) at the time of the outage is called the outage capacity.
Outage Derating Factor	ODF	The ratio of outage capacity to rated capacity is called the outage derating factor. $ODF = Q_o / Q_m$
Scheduled Outage	SO	An outage, which is either planned or which can be deferred until a suitable time
Forced Outage	FO	The state in which the equipment is unavailable for normal operation at its rated capacity (Qm), but is not in the scheduled outage state
Actual Outage Duration	AOD	The time elapsed in decimal hours between the start and the end of an outage is the actual outage duration. The start of an outage is typically the first switching action related to the outage. The end of an outage is typically the last switching action related to return of the equipment to operational readiness
Equivalent Outage Duration	EOD	The actual outage duration (AOD) in decimal hours, multiplied by the outage derating factor (ODF), so as to take account of partial loss of capacity, is called the equivalent outage duration. $EOD = AOD \times ODF$ . <ul style="list-style-type: none"> <li>• Equivalent forced outage duration (EFOD)</li> <li>• Equivalent scheduled outage duration (ESOD)</li> </ul>
Period Hours	PH	The number of calendar hours in the reporting period is referred to as the period hours. In a full year the period hours are 8760, or 8784 in leap years. If the equipment is commissioned part way through a year the period hours will be proportionately less
Actual Outage Hours	AOH	The sum of actual outage durations within the reporting period is referred to as the actual outage hours. $AOH = \sum AOD$ <ul style="list-style-type: none"> <li>• Actual forced outage hours (AFOH), <math>AFOH = \sum AFOD</math></li> <li>• Actual scheduled outage hours (ASOH), <math>ASOH = \sum ASOD</math></li> </ul>
Equivalent Outage Hours	EOH	The sum of equivalent outage durations within the reporting period is referred to as the equivalent outage hours, $EOH = \sum EOD$ <ul style="list-style-type: none"> <li>• Equivalent forced outage hours (EFOH), <math>EFOH = \sum EFOD</math></li> <li>• Equivalent scheduled outage hours (ESOH), <math>ESOH = \sum ESOD</math></li> </ul>
Outage Unavailability	OU	A measure of the MVAR capacity of the controller that was not available is referred as Outage Unavailability <ul style="list-style-type: none"> <li>• Outage Unavailability % <math>OU = (EOH / PH) \times 100</math></li> <li>• Forced Outage Unavailability % <math>FOU = (EFOH / PH) \times 100</math></li> <li>• Scheduled Outage Unavailability % <math>SOU = (ESOH / PH) \times 100</math></li> </ul>
Controller Availability	CA	A measure of equivalent duration for which FACTS CONTROLLER was available at rated capacity. $Controller\ Availability\ \% \ CA = 100 - \%OU$
Outage unavailability due to outages of equipment	AC-E	<b>A.C. and Auxiliary Equipment</b> , all ac main circuit equipment of FACTS controller including ac filters and other reactive power equipment (AC-E.F), ac control & protection (AC-E.CP), interface transformer (AC-E.TX), auxiliary equipment & auxiliary power (AC-E.AX) such as auxiliary transformers, pumps, battery chargers, heat exchangers, cooling system process instrumentation, low voltage switchgear, motor control centers, fire protection and civil works, and other ac switchyard equipment (AC-E.SW) such as ac circuit breakers and disconnect switches.
	V	<b>Valve</b> , all parts of the valves including electrical (V.E), cooling (V.VC), capacitors (V.C) and phase reactor (V.PR) as well as all auxiliaries and components integral with the valve and forming part of the operative array.
	C&P	<b>control and protection equipment</b> , control of the overall FACTS controller system and for the control and protection of each Thyristor Switched Capacitor (TSC), Thyristor Controlled Reactor (TCR) and STATCOM excluding control and protection of a conventional type which is included in "a.c. and auxiliary equipment."
	C	<b>Capacitor banks</b> , fixed capacitors (C.F) and thyristor switched capacitors (C.S). The capacitors related to STATCOM are not included in this category.
	R	<b>Reactors</b> , fixed reactors (R.F) and thyristor controlled reactors (R.S).
	H	<b>Human error</b>
	O	<b>Other</b> , unknown causes
	EXT	<b>External AC System</b> , ac network external to the FACTS controller (not included in the calculation of Forced Outage Unavailability).
Restoration Code	R	Equipment causing outage is repaired or adjusted
	S	Failed equipment is replaced by spare
	M	Manual restart