ACCIDENT REPORT

Report on the investigation of the catastrophic failure of a capacitor in the aft harmonic filter room on board

RMS Queen Mary 2

while approaching Barcelona

23 September 2010

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

LESS SERIOUS MARINE CASUALTY

REPORT NO 28/2011

December 2011

Extract from
The United Kingdom Merchant Shipping
(Accident Reporting and Investigation)
Regulations 2005 – Regulation 5:

"The sole objective of the investigation of an accident under the Merchant Shipping (Accident Reporting and Investigation) Regulations 2005 shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

NOTE

This report is not written with litigation in mind and, pursuant to Regulation 13(9) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2005, shall be inadmissible in any judicial proceedings whose purpose, or one of whose purposes is to attribute or apportion liability or blame.

Front cover photograph (*Queen Mary 2*) courtesy of Jörn Prestien.

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For all enquiries:
Marine Accident Investigation Branch
Mountbatten House
Grosvenor Square
Southampton
United Kingdom
SO15 2JU

Email: maib@dft.gsi.gov.uk
Telephone: +44 (0) 23 8039 5500
Fax: +44 (0) 23 8023 2459

CONTENTS

FIGURES

ANNEXES

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

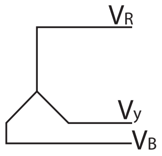
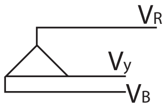
µF	microfarad
ABB	Asea Brown Boveri
AC	alternating current
C	celsius
cm	centimetre
COSWP	Code of Safe Working Practices for Merchant Seamen
CSM	Continuous survey of machinery
DC	direct current
DG	Diesel engine driven generator
DNV	Det Norske Veritas
ECR	Engine control room
EMI	Electro magnetic interference
FSS	International Code for Fire Safety Systems
FWBLAFF	Fixed water-based local application fire-fighting system
GTG	Gas turbine driven generator
GUI	Graphical User Interface
HF	Harmonic filter
HV	high voltage
Hz	hertz
IACS	International Association of Classification Societies
IAS	Integrated automation system
IEC	International electrotechnical committee

IEEE	The Institution of Electrical and Electronic Engineers
IMO	International Maritime Organization
IO	Input-output
IP	Ingress protection
ISM	International Safety Management code
ISO	International Organization for Standardization
K	kelvin
kA	kiloamperes
kg	kilogramme
kV	kilovolts
LR	Lloyd’s Register (Europe, Middle East and Asia)
mA	milliampere
MCA	Maritime and Coastguard Agency
mg/g	milligram/gram
mH	millihenry
ml	millilitre
MOD	Ministry of Defence
mS	millisecond
MSB	Main switchboard
MV	megavolts
MVA	megavolts amperes
MW	megawatts
NK	Nippon Kiji Kyokai

PLC	Private limited company
PMS	Power management system
QM2	Royal Mail Ship Queen Mary 2
RMS	root mean square
RPM	revolutions per minute
SMS	Safety management system
SOLAS	International Convention for the Safety of Life at Sea, 1974
THD	Total harmonic distortion
THDv	Total harmonic distortion of voltage
UPS	Uninterruptible power supply
UTC	Universal Co-ordinated Time
V	volts

Times: All times used in this report are local (UTC+2) unless otherwise stated

LIST OF DEFINITIONS

A-60 division	An A-Class division is a suitably stiffened steel (or equivalent material) bulkhead or deck that is capable of preventing the passage of smoke and flame to the end of a 1 hour standard fire test. When it is insulated such that the average temperature of the unexposed side will not increase more than 140ºC above the original temperature, and that the temperature at any one point will not increase more than 180ºC above the original temperature within 60 minutes, the division is classified as A-60.
Arcing	Uncontrolled conduction of electrical current from phase to ground, phase to neutral, and / or phase to phase accompanied by the ionization of the surrounding air.
Bus bars	An electrical conductor, maintained at a specific voltage and capable of carrying a high current, usually made of copper or aluminium and used to distribute current to multiple devices.
Capacitor	An AC device that stores energy in the form of an electric field.
Delta and star connections	When a three phase voltage supply is connected such that it terminates in a single point, it is called a star connection.  When a three phase voltage supply is connected in a triangle such that each phase forms one side of the triangle, it is called a delta connection. 
Dielectric medium	A medium that is a poor conductor of electricity used between the conducting elements of a capacitor, having the property of retaining electrostatic charge and thereby increasing the capacitance of the capacitor.

Electrical degrees	The unit used to represent the phase difference (in degrees or time) between two electrical wave forms of the same frequency.
Impedance	A measure of opposition to the flow of current in an AC circuit. It is the complex sum of resistance, capacitive reactance and inductive reactance.
Inductor	An inductor (also, reactor) is a passive electrical component that can store energy in a magnetic field created by the electric current passing through it.
Inverse time characteristic	The behaviour of a relay or other electronic switching device which responds within a period of time inversely proportional to the magnitude of the measured signal.
Non-sinusoidal or non-linear current	A current or voltage waveform which does not correspond exactly to the sine wave shape of the supply voltage.
Partial discharge	A localised breakdown of dielectric insulation in a high voltage environment, affecting only a small area and which does not extend to the full distance of the two conductors.
Power converter	An electrical or electro-mechanical device which converts electric power from one form to another.
Pulse	A term used in the AC to DC rectification circuit indicating the number of DC outputs produced from one complete AC cycle.
Reactance	The resistance to current flow in a capacitive circuit is called capacitive reactance while the resistance to current flow in an inductive circuit is called inductive reactance.
Reactive power	The component of electrical power flow which does not perform useful work but which is nevertheless required to drive the real power through capacitive and inductive circuits is known as reactive power.
Reactor	See inductor.
Resonance	The propensity of a system to oscillate with increasing amplitude, limited only by the system’s damping characteristics. Resonance occurs only at certain frequencies and is often triggered by subtle and minor changes in the system.

Sub-transient reactance	The reactance value in motors and generators during the first cycle of a fault current used to calculate the maximum fault current the machine can tolerate. In about 0.1 second the sub-transient reactance increases to transient reactance, and after 0.5 to 2 seconds it reaches the steady state reactance of the machine.
Synchronous motors	An AC motor whose speed varies in direct proportion to the frequency of the supplied voltage.
Thyristor	A semiconductor device used to switch large amounts of electric power with a small triggering current or voltage.
Transformer	A device with two or more electrical windings coupled by a mutually magnetic field.

SYNOPSIS

At 0425 on 23 September 2010, as *RMS Queen Mary 2* (*QM2*) was approaching Barcelona, an explosion occurred in the vessel's aft main switchboard room. Within a few seconds, all four propulsion motors shut down, and the vessel blacked out shortly afterwards. Fortunately, the vessel was clear of navigational hazards and drifted in open sea.

The emergency generator started automatically and provided essential supplies to the vessel, and it was quickly established that the explosion had taken place in the aft harmonic filter (HF) room, situated within the aft main switchboard. The aft main switchboard was isolated, main generators were restarted and the ship was able to resume passage at 0523, subsequently berthing in Barcelona at about 0900. No one was injured.

The accident caused extensive damage to the aft HF and surrounding structure. Two water-mist fire suppression spray heads were activated, one in the aft harmonic filter room and the other in the aft main switchboard room.

The explosion was triggered by deterioration in the capacitors in the aft HF. Internal arcing between the capacitor plates developed, which vaporised the dielectric medium causing the internal pressure to increase, until it caused the capacitor casing to rupture. Dielectric fluid vapour sprayed out, igniting and creating the likely conditions for an arc-flash to occur between the 11000 volt bus bars that fed power to the aft HF.

A current imbalance detection system, which was the only means to warn against capacitor deterioration, was found to be inoperable, and it was evident that it had not worked for several years.

The electrical disturbance from the capacitor failure caused its circuit breaker to open and isolate the aft HF from the electrical network. It was not possible to determine the exact cause of the subsequent blackout because the option for storing historical data concerning blackouts was not chosen at build. However, it is considered most likely that the disruption within the aft HF at the time of the accident caused general instability in the electrical network which could not be contained and led to the generators shutting down.

Lloyd's Register (Europe, Middle East and Asia) (LR) has been recommended to take forward proposals to the International Association of Classification Societies to:

- Establish a requirement for all new vessels fitted with harmonic mitigation equipment to model the effect of its loss and provide data to crew so that appropriate corrective action can be taken in such circumstances.

- Require on-line or periodic monitoring of harmonic distortion of voltage on all vessels with high voltage power systems to give early warning against potential problems.

- Develop requirements to detect and mitigate against the failure of high-energy storage devices and to ensure that protection devices of critical items are fail safe.

LR has also been recommended to review its rules on the use of water-based fire-fighting systems in areas containing high voltage equipment and to work with the International Association of Classification Societies to propose appropriate guidelines to the International

Maritime Organization for inclusion in the International Code for Fire Safety Systems. The Maritime and Coastguard Agency has been recommended to produce specific guidance regarding the harmful effects of excessive harmonic distortion in electrical networks and to update the Code of Safe Working Practices for Merchant Seamen to raise awareness about the hazards of arc-flash in high voltage equipment.

QM2's manager, Carnival UK have also been recommended to: improve the standards of protection against the effect of harmonic distortion and component failure; and, to review the machinery alarm systems fitted to *QM2* in order to identify and prioritise those alarms which indicate failure conditions that could significantly affect the safety of the vessel.

Photograph courtesy of Jörn Prestien

Queen Mary 2

SECTION 1 - FACTUAL INFORMATION

1.1 PARTICULARS OF *RMS QUEEN MARY 2* AND ACCIDENT

SHIP PARTICULARS

Flag	United Kingdom
Classification society	Lloyd’s Register
IMO number	9241061
Type	Passenger cruise liner
Registered owner	Carnival PLC
Manager(s)	Carnival PLC
Construction	Steel
Length overall	344.3m
Gross tonnage	148528
Propulsion (power)	Diesel electric (4 x 21.5MW)

VOYAGE PARTICULARS

Port of departure	Southampton
Port of arrival	Barcelona
Type of voyage	International voyage

MARINE CASUALTY INFORMATION

Date and time	23 September 2010 at 0425
Type of marine casualty or incident	Less Serious Marine Casualty
Location of incident	40º 44.36N, 001º 49.42E, 36nm SW of Barcelona
Place on board	Aft harmonic filter room
Injuries/fatalities	None
Damage/environmental impact	Two capacitors damaged, bus bars and insulators on several others damaged, bulkhead stiffeners buckled, enclosure panel doors blown out, steel doors damaged.
Ship operation	On passage
Voyage segment	Mid-water
Persons on board	3823 at time of accident

1.2 BACKGROUND

QM2 was propelled by four variable speed electric motors known as ‘podded drives’. The variation of speed was achieved by changing the electrical frequency in the power supply to the motors. An unwanted effect of varying the frequency was distortion of the supply voltage waveform. The degree of distortion was quantified as total harmonic distortion and had to be maintained within limits defined by the vessel’s classification society. On *QM2*, this was achieved by using harmonic filters (HF); HF units, consisting of a tuned load of capacitors and inductors, were connected to the forward and aft main switchboards (MSB). Each HF consisted of two sections, known as rank 11.3 and rank 4 **(Figure 1)**.

The MSBs were connected to each other through circuit breakers **(Figure 2)**. Each HF was located inside a separate room within the MSB compartment. Both MSB and HF compartments were protected by a water-mist based local application fire-fighting system known by its trade name as *Hi-Fog*.

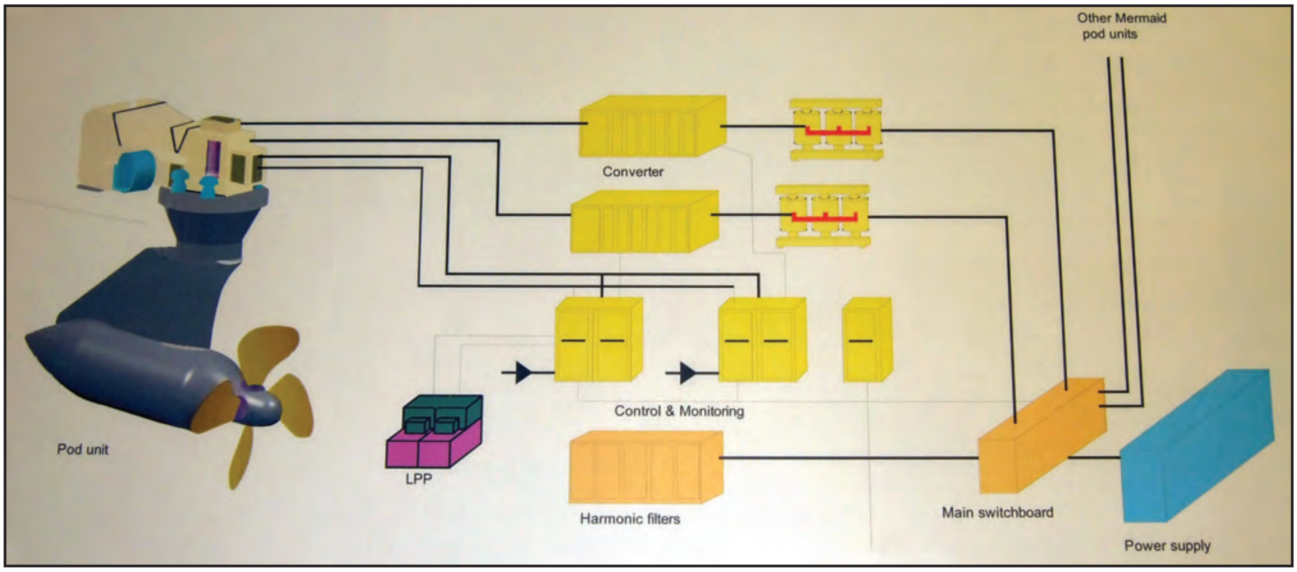
1.3 NARRATIVE

At 0415 on 23 September 2010, the watchkeeping officer on the bridge of *QM2* gave 2 hours’ notice to the engine room watchkeeper in preparation for arriving at Barcelona **(Figure 3)**. The vessel had departed from Southampton on 19 September and was on a course of 026º at a speed of 18.6 knots with all four podded drives running. There were four engineers in the engine control room (ECR) including two from the previous, offgoing watch. Just after 0425 they heard a loud bang, which was followed by complete failure of the engine room lighting except the transitional lighting. Almost immediately, the main propulsion motors’ output power dropped down to under 5MW and the motors stopped approximately 16 seconds later when all the generators shut down.

The emergency generator started automatically and restored lighting and other essential supplies. The third engineer from the offgoing watch ran to investigate and soon discovered thick black smoke coming from the aft MSB room. Alerting the other engineers in the ECR with his portable ultra high frequency radio, he closed the watertight door between the engine room and the space which led to the aft main switchboard room. He also prepared a fire hose and laid it at the entrance to the watertight door. Several smoke and heat detection sensors from the aft HF and the aft MSB rooms were activated.

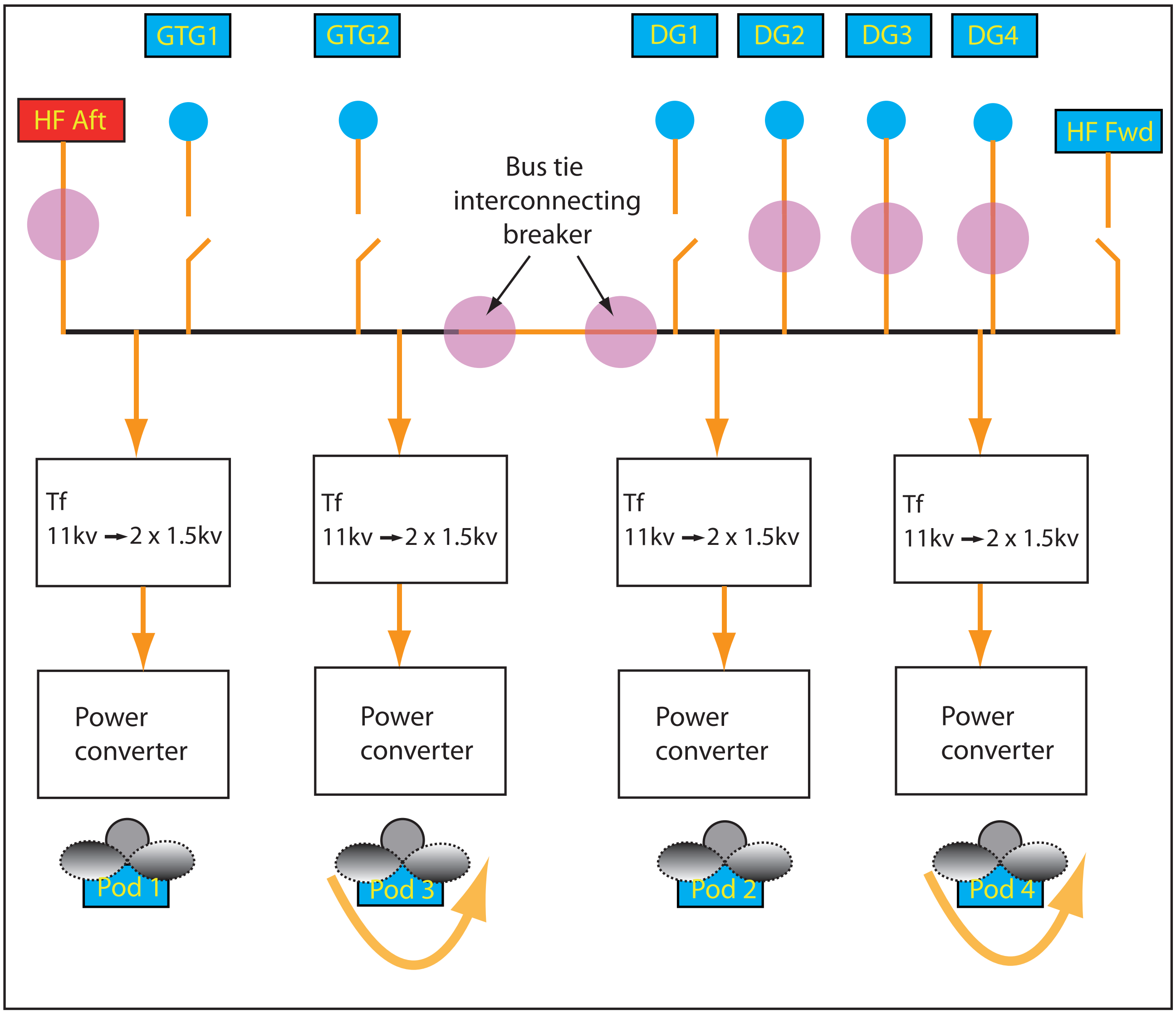
At around 0430, the bridge team mobilised the assessment party, which comprised six senior representatives from the deck, engine and hotel departments. The deck and engine fire parties, together with the boundary cooling party (a total of 26 personnel) stood by, along with all the hotel managers who were specifically tasked to deal with passenger queries. No passenger or general crew announcement was made. The ‘not under command’ lights were switched on and the Spanish coastguard was informed.

Figure 1



Propulsion system and harmonic filter

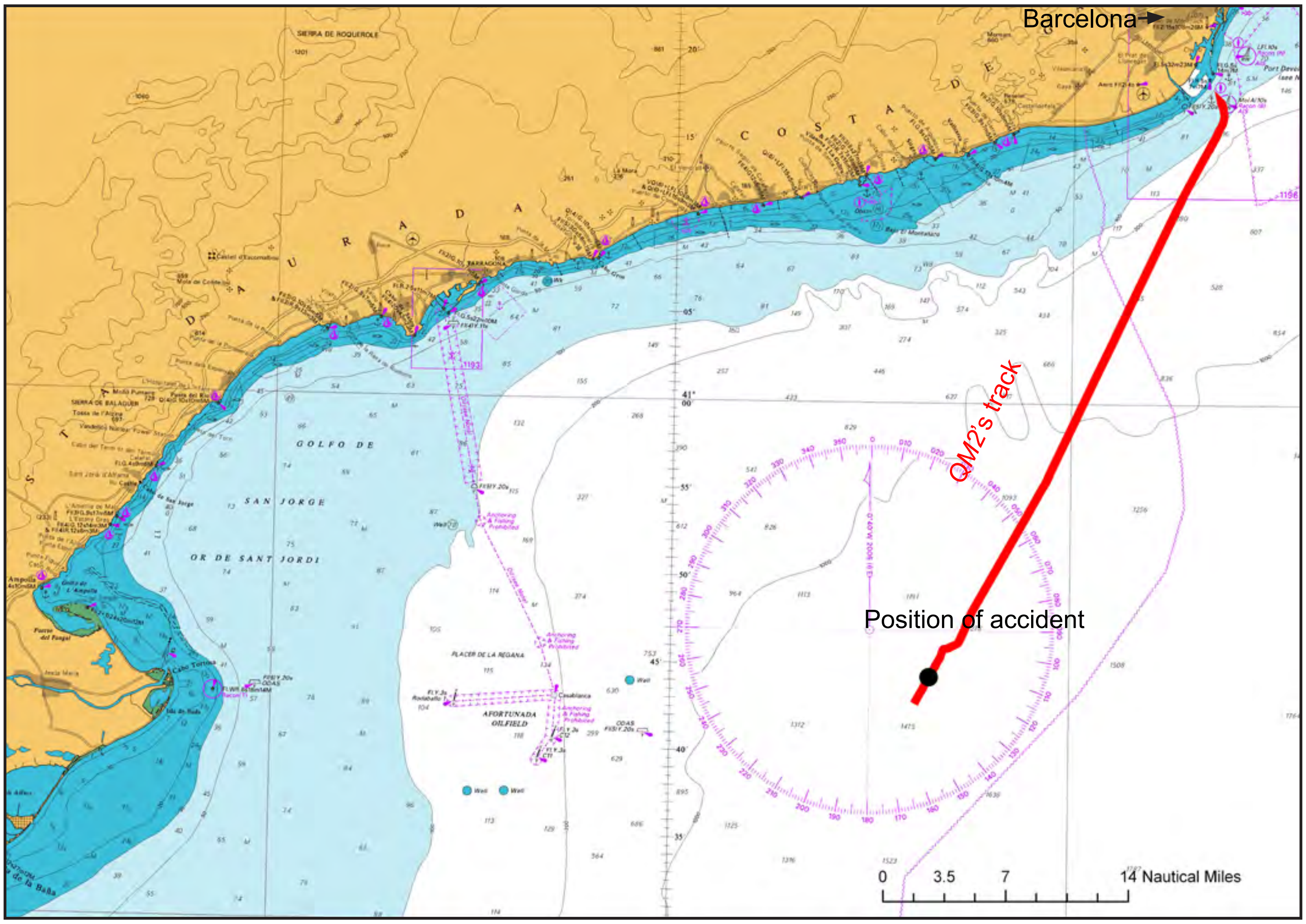
Figure 2



High voltage electrical network

Reproduced from Admiralty Chart 1704 by permission of the Controller of HMSO and the UK Hydrographic Office

Figure 3



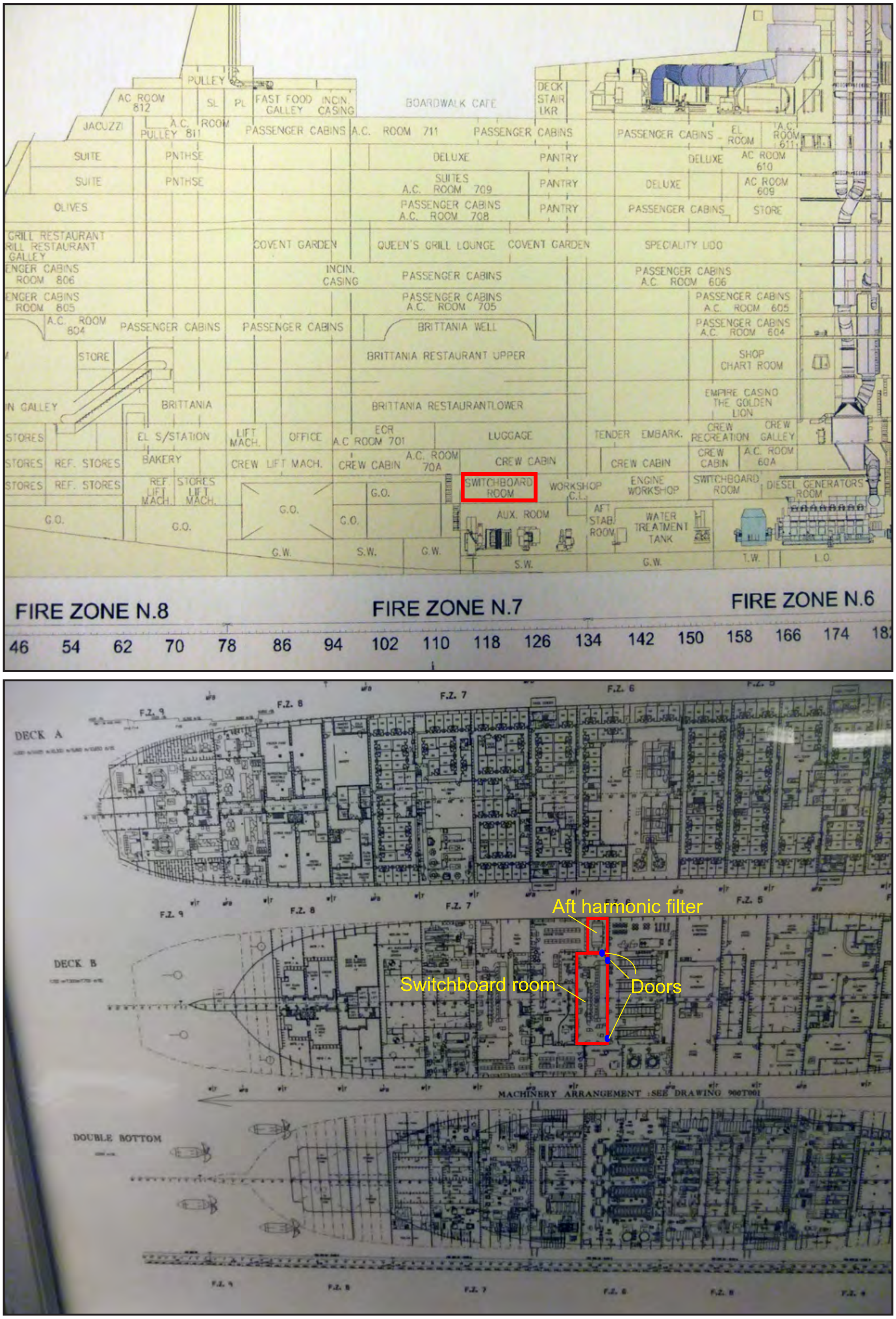
Position of *QM2* at the time of the accident

By 0439, the second electro-technical officer and a third engineer, both wearing breathing apparatus and carrying carbon dioxide portable fire extinguishers and a thermal imaging camera, were ready to carry out an inspection of the scene. They entered the aft MSB room and made their way into the HF room, stopping just after entering the doorway **(Figure 4)**. They confirmed that the space was filled with thick black smoke; but there was no fire and, using their thermal imaging cameras, they did not detect any hot spots. Two *Hi-Fog* glass bulbs **(Figure 5)**, one in the aft HF room and another in the aft MSB room had ruptured and there was approximately 10mm of water on the decks of both compartments **(Figure 6)**.

The crew attempted to shut off the *Hi-Fog* water supply using the manual shut-off cock located outside the aft MSB room; but they were unsuccessful as the handle sheared when they tried to force it. The *Hi-Fog* system was then switched off at the central control station, and at 0452 extraction fans were started to clear the smoke.

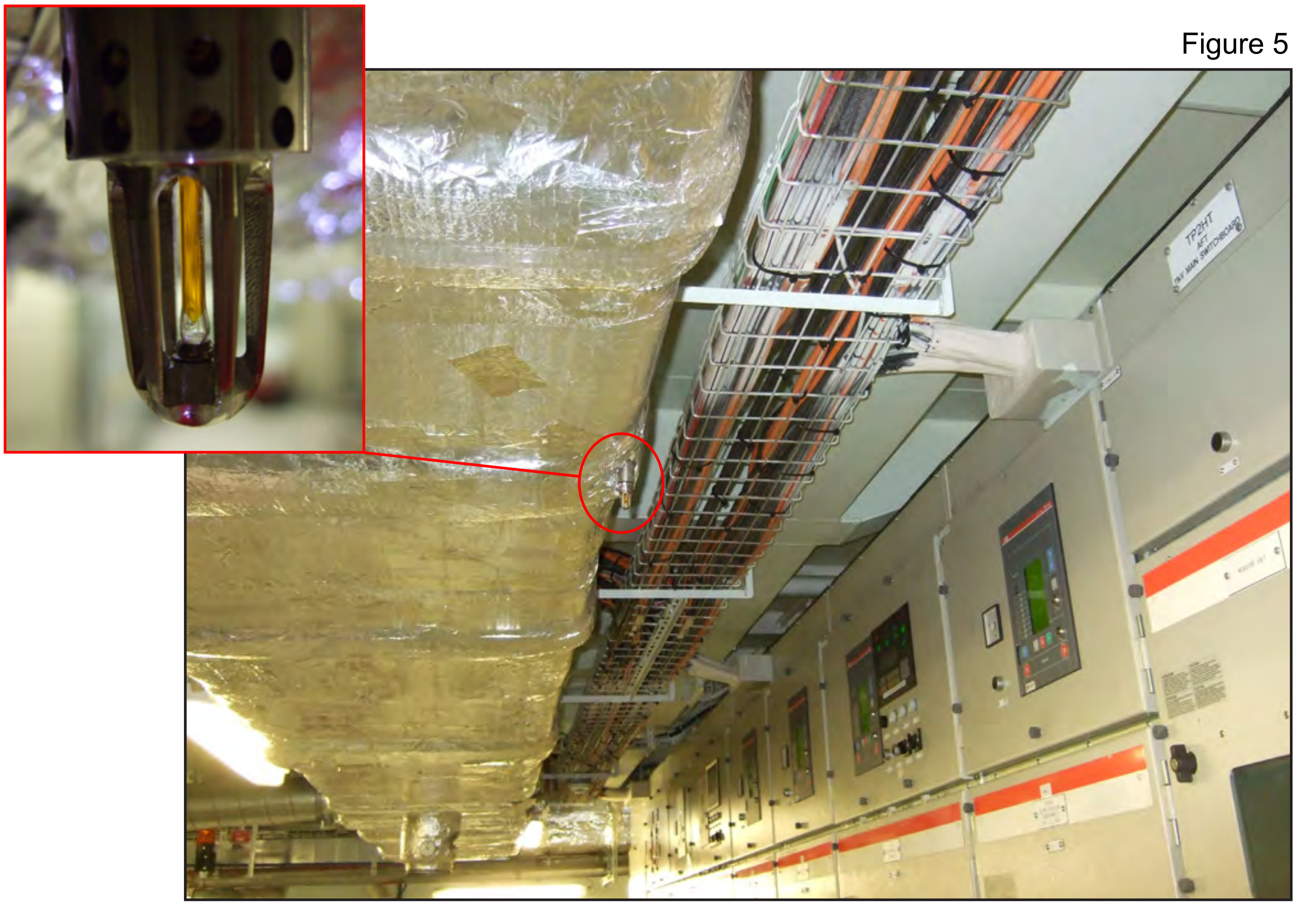
By 0455 three diesel generators had been started and connected to the forward MSB; the aft MSB was kept isolated by disconnecting the bus tie breakers between the two switchboards **(Figure 2)**. By 0523 *QM2* was underway using pods 2 and 4, and the vessel berthed at Barcelona just before 0900. Representatives of Converteam, the manufacturer of the HF and propulsion drive, and Lloyd's Register (Europe, Middle East and Asia) (LR) the classification society for the vessel, carried out a detailed assessment once the vessel was alongside. They concluded that, after physically removing the circuit breaker between the MSB and the HF, it was safe to put the aft MSB back on-line. LR imposed a condition of class on the vessel, to remain until the aft HF issue was repaired. At around midnight, the vessel sailed from Barcelona.

Figure 4



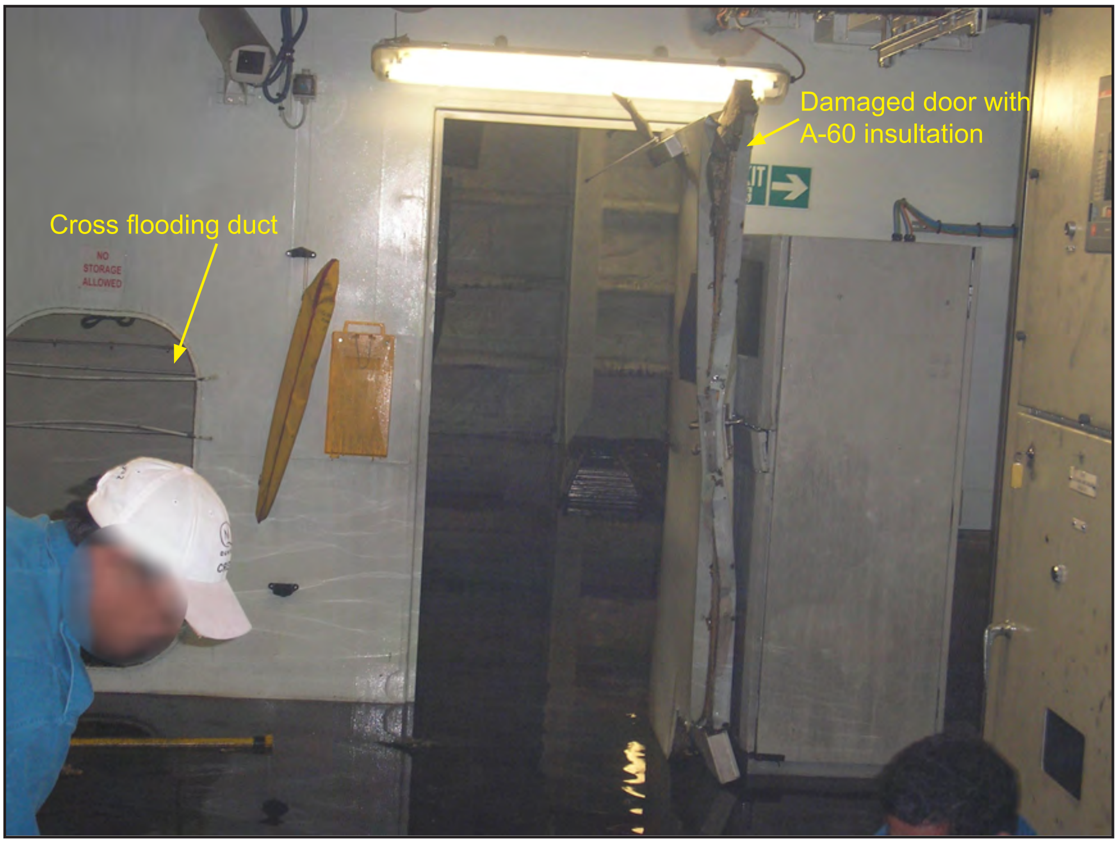
Location of harmonic filter

Figure 5



Hi-fog glass bulb in the aft main switchboard room

Figure 6



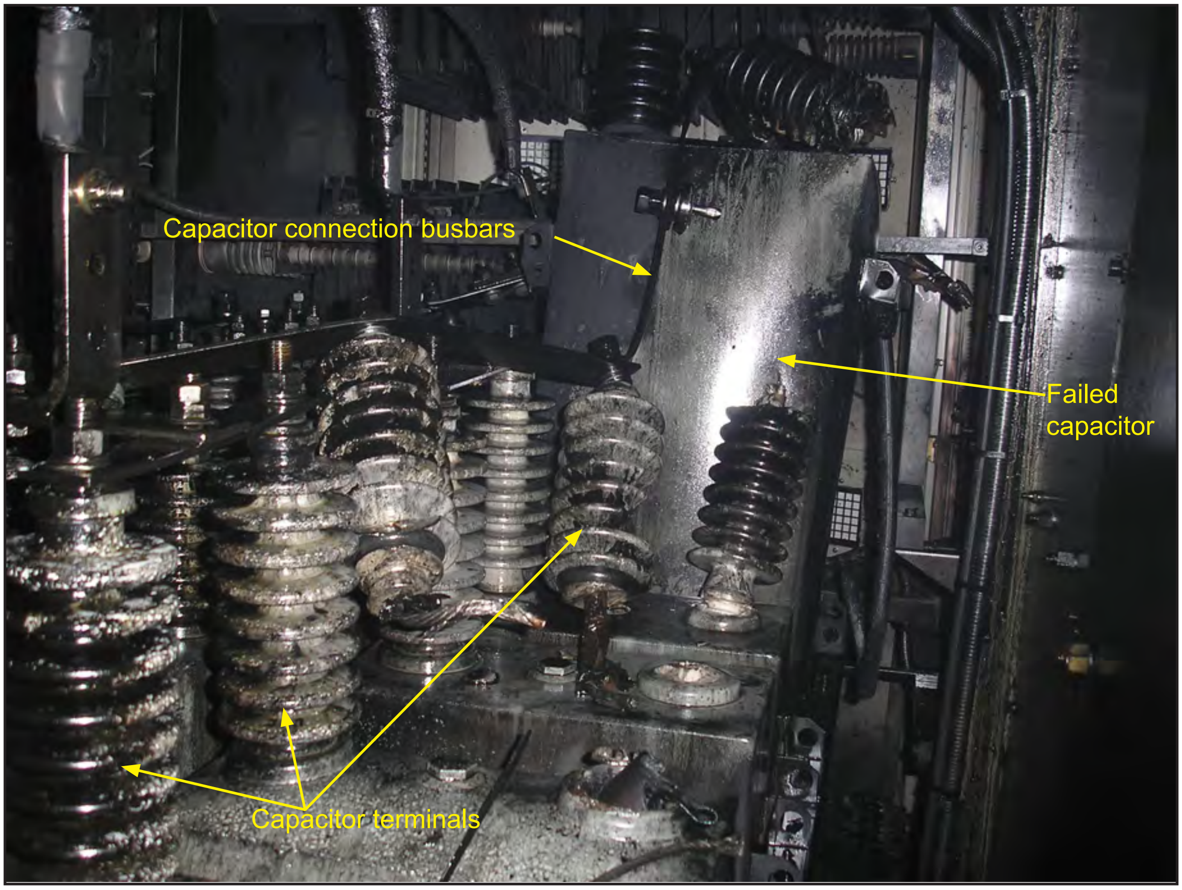
Water in the aft harmonic filter and main switchboard rooms

1.4 DAMAGE

The damage in the aft HF room was extensive. Most of the occupants of the six crew cabins located directly above the aft HF room heard the noise of the blast and described the sound as a 'loud bang'. There was no damage inside their cabins. Panels on either sides of the rank 11.3 cubicle were badly distorted and covered with soot. Panels for the rank 4 cubicle were also bulged out. The floor and deckhead were covered with soot and dielectric oil was found all over the rank 11.3 HF section, including the area under the capacitors and on the inside of the top panel of the enclosure. One capacitor was found to have lifted up around 60cm from its normal position. Its bottom cover had bent outwards and blown out at its welded joint. It had wrenched itself free from its foundation bolts, breaking the connection to the capacitor elements inside. All the capacitors fitted in the same row as the failed one had suffered damage on their terminals. The casing of another capacitor was found to have bulged severely **(Figure 7** and **Figure 8)**.

The 'A-60' rated steel door to the compartment was found forced out through its frame and the adjoining steel door for the MSB room was also buckled and split. A steel door at the inboard entrance to the aft MSB room and located approximately 20m away from the site of the explosion was forced off its hinges. The stiffeners on the bulkhead of the compartment were buckled and the steel cover plate on the cross-flooding duct between the HF and MSB rooms was blown out into the MSB room. The polythene covering on a fire extinguisher, which was located approximately 2m away from the failed capacitor, was found singed. The corners of all three high voltage bus bars that fed into the aft HF had been melted **(Figure 9)**.

Figure 7

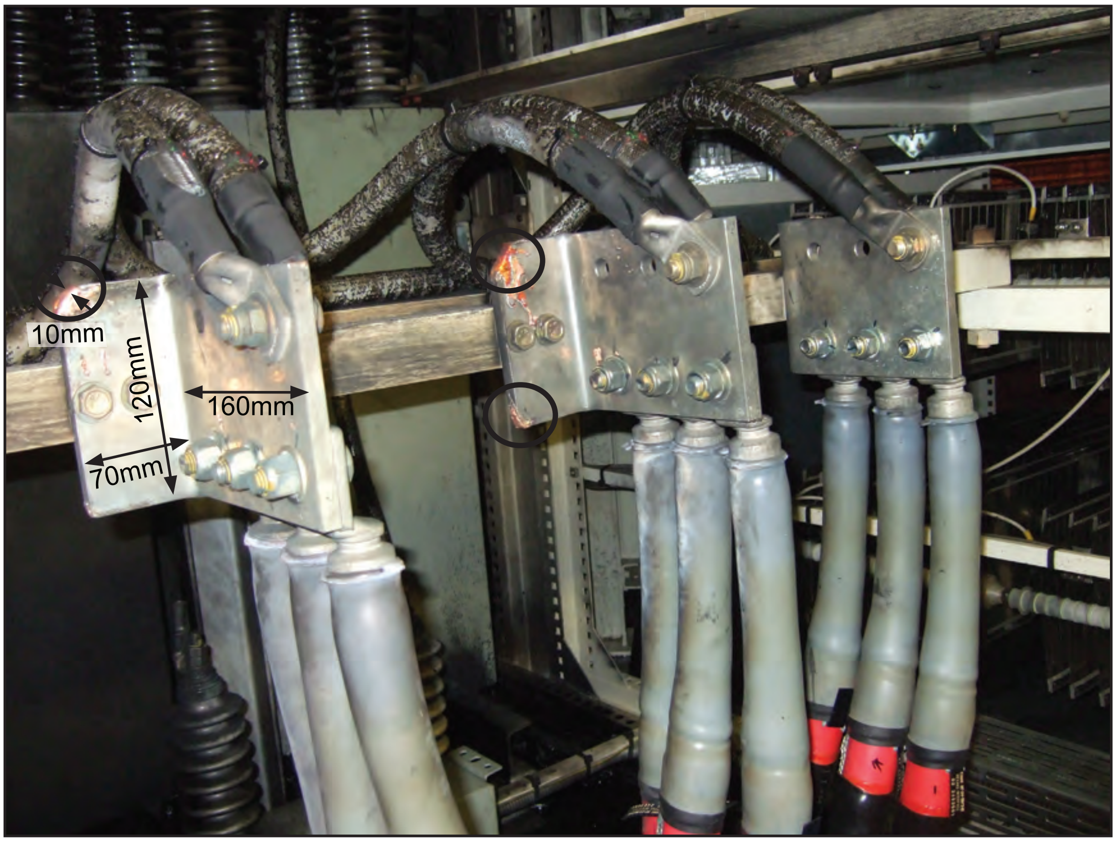


Failed capacitor

Figure 8

Top view of bulged capacitor

Figure 9



Evidence of arcing on the harmonic filter bus bars

1.5 VESSEL MANAGEMENT

QM2 conducted sea trials in September and again in November 2003. The vessel was formally handed over to Cunard Line (a division of the Carnival Corporation) in December 2003, commencing her maiden voyage on 12 January 2004. From 2004 to 2007 technical management was carried out by Princess Cruises International, Los Angeles, which was also a division of the Carnival Corporation. In November 2007 technical management was transferred to Carnival UK based in Southampton.

Two technical superintendents looked after the vessel's day-to-day mechanical and electrical requirements respectively. All routine requests from the vessel for spare parts were co-ordinated and approved by the appropriate superintendent. The vessel's Amos Computerised Maintenance Management System kept a running record of spare parts usage and also had a minimum balance function to maintain a stock of critical spare parts. It did not have the functionality to identify trends for abnormal consumption of spare parts. A minimum of one spare capacitor for each of the two HF ranks was required to be kept on board.

1.6 ELECTRICAL SYSTEM

1.6.1 Power generation and distribution

QM2 had a total power production capacity of 135MVA at 11kV (60Hz) alternating current (AC). Two gas turbine driven generators (GTG) supplied the aft MSB and four diesel engine driven generators (DGs) supplied the forward MSB. At the time of the accident three DGs were sharing the power requirement. One GTG was out of order.

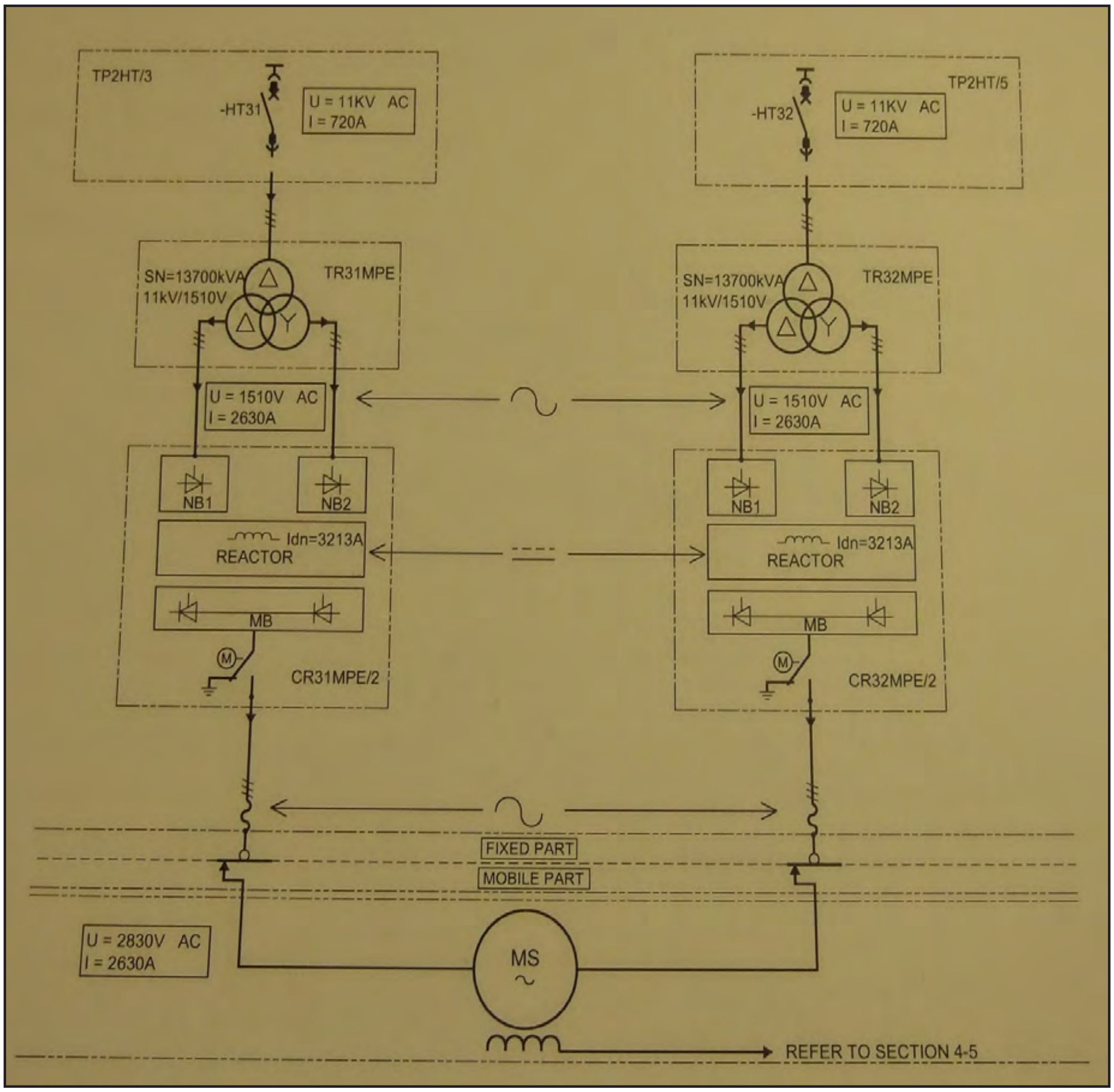
In normal operation, the MSBs were always connected to each other through the two bus tie circuit breakers. The auxiliary machinery was supplied at 690V, with the exception of the air conditioning compressors and bow thrusters, which were rated at 11kV. The main propulsion motors were of synchronous type, supplied through step down transformers and power converters. Each motor consisted of two independent sets of windings (half motors) operating within a frequency range of 0 to 15.8Hz (0 – 137RPM) and voltage range of 0 to 2830V, which varied in linear proportion to the frequency.

1.6.2 Propulsion transformers and power converters

The propulsion transformers stepped down the voltage from 11kV to 1510V. Each had a delta connected primary winding and two secondary windings: one star wound and the other delta wound. The delta and star connections generated a phase difference between their voltage outputs of 30 electrical degrees.

There were eight power converters, one for each half motor, with one connected to the output of each secondary coil of the transformer. The converter consisted of a network bridge, which rectified the 1510V AC to a direct current (DC); a DC link, which included an inductor coil of 5.5mH designed to damp surges and eliminate current transients; and a motor bridge which inverted the DC supply into an AC waveform of variable frequency and voltage. Both the network and motor bridges were thyristor controlled and supplied the synchronous motors at a frequency to provide the required propeller speed. The electrical phase shifting achieved by the delta-star transformer secondary winding output, combined with the full wave rectification process resulted in 4 pulses per phase and 12 pulses for the 3 phase supply to the motor. The power converter was therefore called a 12 pulse converter **(Figure 10)** and was selected because of its lower level of harmonic distortion compared with other types of converters.

Figure 10



Power converters for propulsion motors

A ‘Buchholz’ gas actuated pressure detection relay, with an inverse time characteristic, monitored changes in the vapour pressure inside the transformer oil tank. It was set to raise an alarm and disconnect the transformer electrically if a fault occurred that caused the oil vapour pressure to rise. The oil in the propulsion transformers was tested regularly for the presence of dissolved gases to detect arcing or partial discharge and provide an indication of the condition of the transformer.

1.6.3 Main circuit breakers and protection devices

All the circuit breakers and their protection relays were supplied by Asea Brown Boveri (ABB) Sace. Each HF had its own circuit breaker of type HD4/C which had a voltage rating of 12kV and a current rating of 1600A with a breaking capacity of

50kA. In addition to overcurrent and short circuit protection, the breaker had an undervoltage protection trip. The circuit breaker could also be tripped by overload current sensors in the HF itself. These were supplied and fitted to the ABB breakers by Converteam. Deterioration of the capacitors in the HF was monitored by measuring the current imbalance between the capacitors in each of the three phases. Discussed in more detail later in the report, detection of an unbalanced current between the capacitors was also designed to trip the relevant HF circuit breaker.

There were two bus tie interconnecting breakers, one on each MSB and rated at 12kV, 3600A with a breaking capacity of 50kA. The tie breakers had short circuit, overcurrent, and overvoltage protection trips, but did not have an undervoltage trip function. Immediately after the accident, the bus tie breaker in the forward MSB was found tripped. The second bus tie breaker was found in the closed position.

All the DG supply breakers were rated at 11kV and 1000A. The generators were protected by two relays known as ‘Synphol D’ and ‘Ref 542’ with the overcurrent trip function being duplicated in both relays. In addition, there were several instant trip functions to protect generators against internal faults.

In case of serious faults in the connected loads, the protection relays were configured to trip the bus tie interconnector closest to the generators. If the fault did not clear by tripping the bus tie, the generator breakers themselves would trip. The protection system also monitored overcurrent, negative sequence (phase imbalance), under / over frequency and overvoltage parameters. Imbalance or negative sequencing was detected when any connected load was open circuited in one phase causing an asymmetric phase fault (known as single phasing). The alarm indicating negative sequencing was provided by the relay ‘Synphol D’.

The protection relays were capable of storing a record of why each trip had occurred. However, the option for storing historical data concerning blackouts was not chosen at build and the information which could have identified why the generators shut down was not recorded.

1.6.4 Selectivity study

A selectivity study, also known as a discrimination study, was carried out during the design phase for *QM2* as part of LR’s requirements for plan approval. Its purpose was to demonstrate that the protective relays for circuit breakers throughout the network had been set such that if a fault occurred in one part of the network, the circuit breaker closest to the fault would open first to isolate the fault and protect the rest of the network. The selectivity study for *QM2* was approved by LR in April 2003. The protection settings of all the 11kV circuit breakers were tested by the secondary current injection method during a dry docking period in October 2008.

Immediately after the accident, the MAIB requested that Carnival UK check the settings on the protective relays of the HF, interconnecting bus tie and generator breakers with the assistance of the system manufacturers, ABB. Although ABB was tasked to carry out this job, it had not been carried out by the time this report was being finalised.

1.7 AUTOMATION AND POWER MANAGEMENT

1.7.1 Integrated automation system

The Integrated Automation System (IAS) was provided by Valmarine AS, Norway and was based on its Damatic XD system. A local area network of computers permitted the ship's crew to monitor the majority of ship's machinery from stations located around the ship and to control them from certain locations, such as the ECR and wheelhouse workstations. It also provided the machinery alarm system for the vessel through four alarm stations.

The fire detection and alarm system was independent; however it provided an input to the IAS indicating the deck on which a fire detection sensor had been activated. Two fire alarms, one from the accommodation and the other from the engine room, appeared on the IAS approximately 30 minutes before the accident. There were no corresponding alarms on the fire detection system panel. At the request of the MAIB the ship's crew investigated the source of this fire alarm and established it to be spurious, due to a wiring defect on the IAS.

1.7.2 Alarm sampling sequence and history

The execution cycles for the alarm handling stations were at 400ms intervals for everything related to 11kV systems and for those which were part of the power management system (PMS). Less critical alarms were monitored at 1100ms intervals and all other binary alarms, not related to the PMS, were sampled at 900ms intervals. The alarm input-output (IO) card at the alarm processing station would cycle through the alarm channels and hold each alarm in a buffer, allocating them all with the same time stamp. Therefore the time stamp indicated on the alarm printout was not always the exact time that the alarm was triggered.

In the 10 minutes during and immediately after the explosion there were nearly 500 alarms registered on the IAS. In the midnight to 0400 hours watch on 23 September, a total of 468 lines were printed on the ECR alarm printer, of which 235 were critical or non-critical alarms. The remainder were records of the alarms being acknowledged.

It was not possible to establish whether the aft HF circuit breaker tripped due to an overload in either rank, or due to an imbalance in its rank 4 section as the AIS did not differentiate between the two types of alarms and recorded it as an 'overload/unbalance'. It is known, however, that within 300ms to 500ms of the alarm, the circuit breaker opened. Almost simultaneously or just before the circuit breaker opened, there were several 'IO-FAULT' alarms (indication of loss of reactive power) at both high voltage switchboards and generators. There were also several 'DISCREPANCY' alarms (indication that the switchboard had detected a loss of one phase) at several bus bars in the 690V circuit. No undervoltage alarms in either the high or low voltage circuits were registered by the IAS.

1.7.3 Propulsion system alarm log

The propulsion system had its own monitoring system, provided by Converteam, called P1200, which communicated important alarms to the IAS. At approximately 0348 the alarm 'half drive alarm lamp' for propulsion motor no. 3, half drive no. 2 came up on the P1200 system. The same alarm reappeared at around 0356, 0405 and 0406. This alarm indicated that a fault was detected in this particular half drive and was intended to be a precursor to the more specific alarms which would follow. While all the alarms on the P1200 system were available to engine room watchkeepers, the IAS was considered to be the primary alarm system.

Immediately after the HF circuit breaker tripped at around 0425, alarms activated indicating problems with all of the propulsion motor converters and excitation systems. The propulsion system P1200 alarm log indicated that all the four propulsion motors registered undervoltage alarms immediately after the HF breaker tripped. However, these were very short term and the actual voltage levels were not recorded by the P1200 system or transferred to the IAS. The motors themselves continued to run under reduced power for approximately 16 seconds after the undervoltage alarms until the generators themselves shut down **(Figures 11a** and **11b)**. An annotated record of alarms from the IAS and from the P1200 system for propulsion is available at **Annex A**.

1.7.4 Power management system

The power management system (PMS) was a function of the IAS. It controlled the start, stop, auto synchronisation and load sharing functions of the generators. However, it was not designed to have any input from the protection relays of generator main circuit breakers, and did not reduce propulsion power or react in any way to the failure of harmonic filters.

1.8 HARMONICS

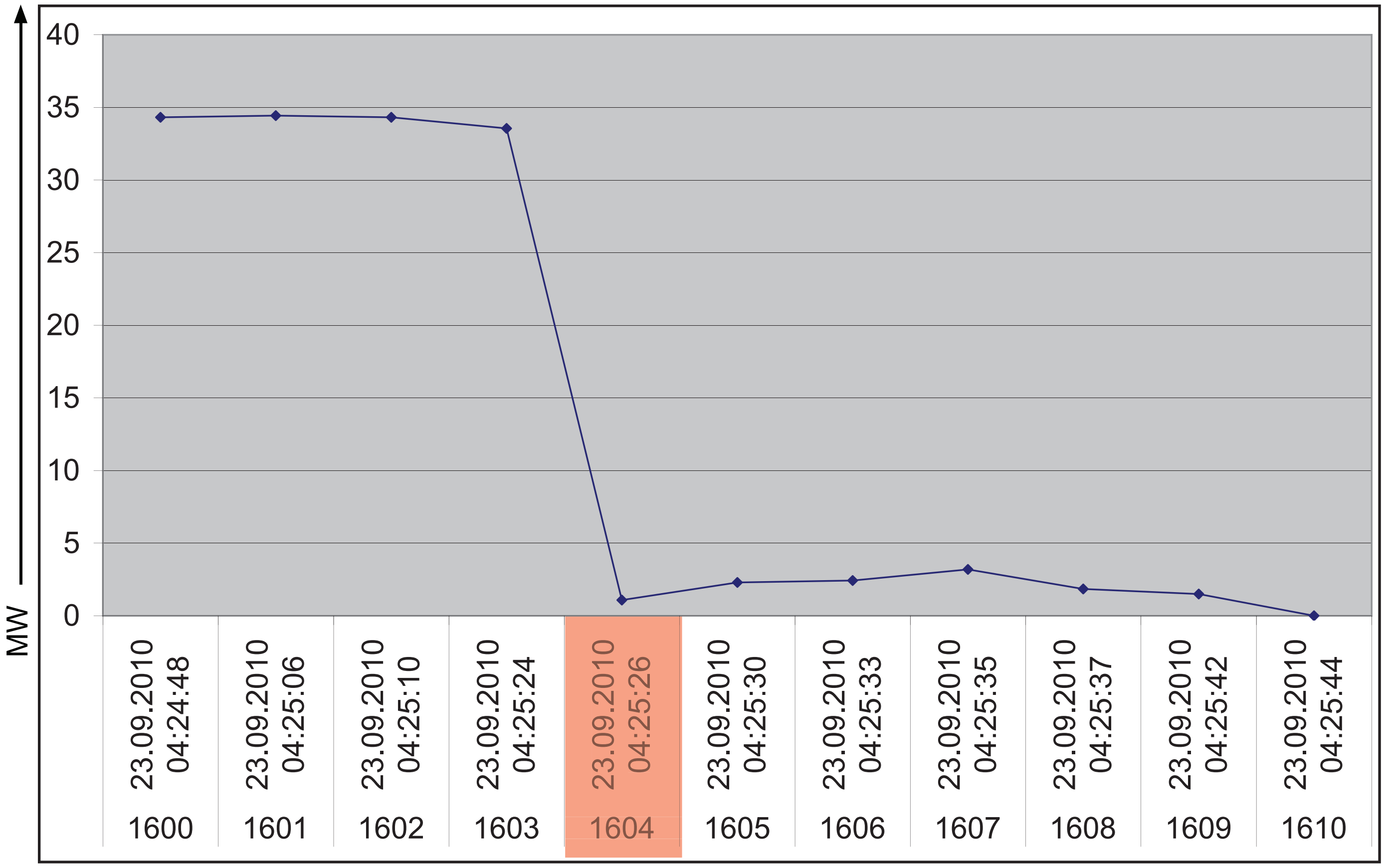
1.8.1 Harmonic distortion

When an AC electrical load draws non-sinusoidal or non-linear currents, it tends to distort the waveform of the supply voltage. The switching action of thyristors in the power converters results in non-sinusoidal currents being drawn from the generators. While the supply originally delivers a ‘clean’ sinusoidal voltage at the fundamental frequency of 60Hz the power converters, in drawing a distorted current, cause the supply voltage from the generators to distort. This generates voltages at the harmonics of the fundamental frequency, which in turn affect all the connected loads regardless of whether they are linear or non-linear. In marine and offshore installations, electric variable speed drives are the main source of harmonic distortion to current and voltage waveforms.

1.8.2 Harmonic distortion in marine systems

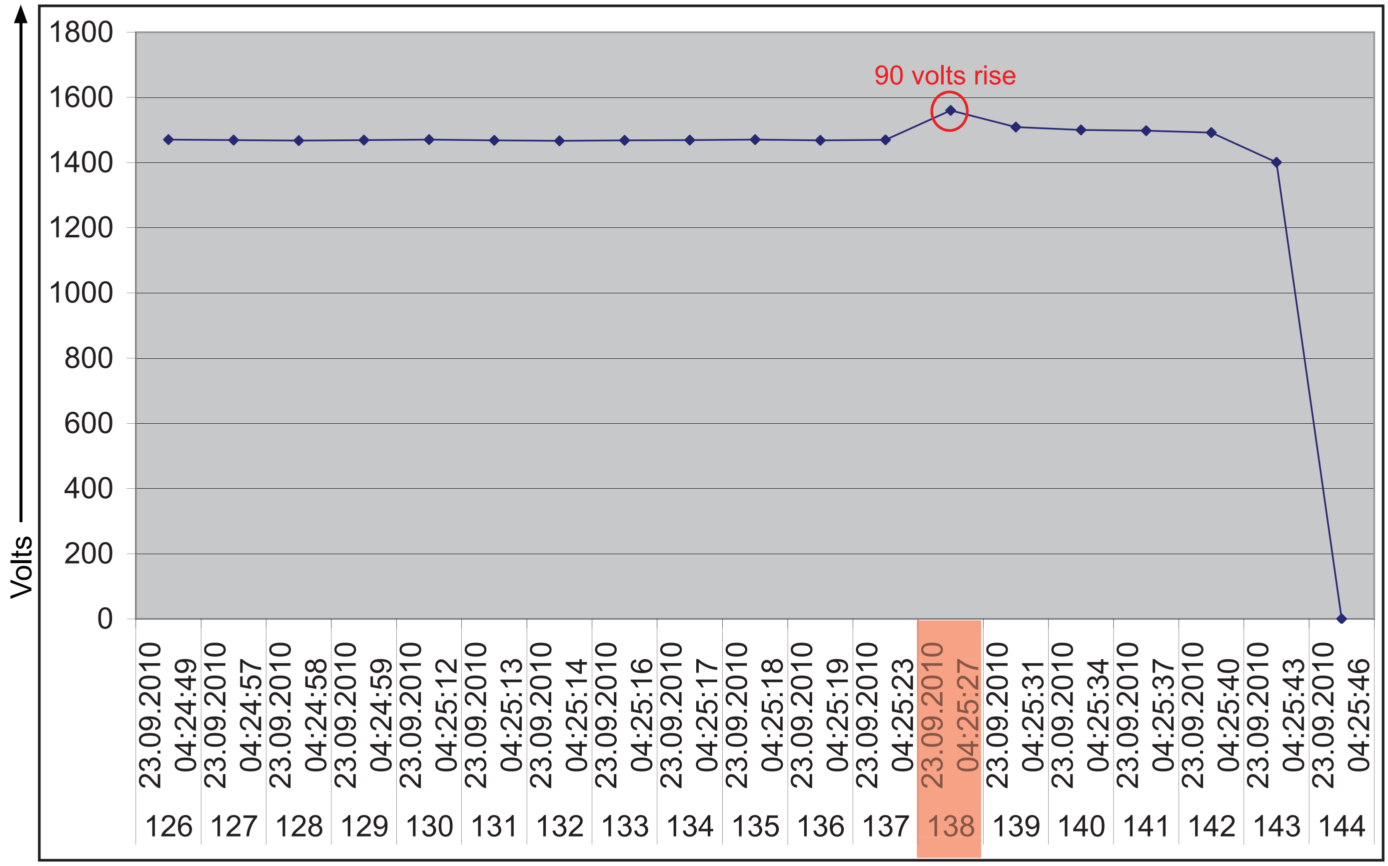
Power converters produce harmonics at frequencies according to the relationship np ± 1 where n is a positive integer and p represents the number of pulses in the power converter. Therefore, for the 12-pulse converters fitted on *QM2* the predominant harmonics were at the multiples 11, 13, 23, 25, 35, 37 and so on of the fundamental frequency (60Hz). In a land-based generation system, the distortion of current due to non-linear loads does not result in significant voltage distortion at source because these loads are a minor fraction of the total power generation capacity. Consequently, the effects remain local to the non-linear load. On an electrically propelled vessel, such as *QM2*, the propulsion motors consume more than 70% of the total generated power and the resulting voltage distortion is more significant. The impedance of a marine generator is also normally quite high compared to that of the utility’s transformer. This results in a larger voltage distortion at the source

Figure 11a



Generators’ power output

Figure 11b



Variation of voltage at propulsion motor no.1 half drive motor no.1 immediately after capacitor explosion when harmonic currents are drawn by substantial non-linear loads such as the main propulsion motor power converters. As more generators are added to increase the power generated, they also have the effect of lowering the overall impedance, reducing the amount of harmonic distortion.

1.8.3 The harmful effects of harmonics

Excessive harmonic distortion of current and voltage can cause heating in the windings of transformers, generators and induction motors, which could potentially result in fire. Some of the other more common and unpredictable effects of excessive harmonic distortion are:

- Disruption in the operation of uninterruptible power supplies (UPS)
- Spurious tripping or failure of sensitive electronic and computer equipment, measurement and protection relays
- Voltage resonances leading to transient overvoltage and overcurrent failures in the electrical network
- Electro magnetic interference (EMI) resulting in disruption to communication equipment
- Malfunction of circuit breakers and fuses.

1.8.4 Total harmonic distortion

Total harmonic distortion (THD) of voltage and current is the ratio used to describe the distortion in the electrical power generation and distribution system. It is calculated by the ratio of the root mean square (RMS) value of the harmonic content to the RMS value of the fundamental. It is normally expressed as a percentage, calculated using the expression:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100$$

where

V_h = RMS amplitude of voltage at harmonic order h

V_1 = RMS amplitude of the fundamental voltage.

LR’s rules on harmonic distortion of voltage state:

> *Unless specified otherwise, the total harmonic distortion (THD) of the voltage waveform at any a.c switchboard or section-board is not to exceed 8 per cent of the fundamental for all frequencies up to 50 times the supply frequency and no voltage at a frequency above 25 times supply frequency is to exceed 1.5 per cent of the fundamental of the supply voltage.*

All other classification societies place a limit of 5% on THD of voltage (THDv).

The Institution of Electrical and Electronic Engineers' (IEEE) Recommended Practice for Electrical Installations on Shipboard (IEEE Standard 45-2002), states:

> *A dedicated propulsion bus should normally have a voltage total harmonic distortion of no more than 8%. If this limit is exceeded in the dedicated propulsion bus, it should be verified by documentation or testing that malfunction or overheating of components does not occur. A non-dedicated main generation/ distribution bus should not exceed a voltage total harmonic distortion of 5%, and no single voltage harmonic should exceed 3%.*

IEC 60034-1, 2004, Rotating Electrical Machines - Part 1: Rating and Performance, requires that the THDv for synchronous motors above 300kW output should not exceed 5%. It does not specify distortion levels for individual harmonics.

1.8.5 QM2 sea trials and system modelling

Converteam carried out simulations of *QM2*'s electrical system in 2002 and calculated the THDv with one and two HFs in the circuit and different numbers of generators on load. The simulation predicted the worst case would be 7.6% THDv. Sea trials were performed in 2003 to ensure that THDv was within 8% in both high and low voltage sections of the electric network on board. THDv was measured up to the 49th harmonic under several different power conditions ranging from two to six generators on-line and the maximum speed possible in each configuration. The worst case was recorded with the combination of one HF with two DGs; THDv at the 11kV bus bar was recorded as 3.4%, and at the 690V bus bar as 6.5%. No trials or simulations were carried out without the harmonic filters connected to the system. No trials were carried out with three DGs and one HF, the combination being used at the time of the accident.

Harmonic distortion was not routinely measured in service as the crew were not aware that they had the appropriate measuring equipment on board. After the accident, the crew found the equipment and used it to measure the THDv on the vessel. Their report concluded that THDv was generally less than that calculated by Converteam during the sea trials, although they reported that the 35th and 37th harmonics exceeded LR's requirements of 1.5% for those harmonics above the 25th harmonic order.

The MAIB commissioned a specialist power quality testing and monitoring company, Harmonic Solutions Co. UK, to carry out THDv measurements while *QM2* was on passage during the period 8 to 11 December 2010.

Table 1 shows the comparison of the measurements recorded in the later tests with those recorded during the sea trials in 2003 when a single harmonic filter was in circuit with four DGs and one GTG generator supplying the load.

Condition	MAIN CIRCUIT BREAKERS						Comments
4 x DG + 1 x GTG (one HF in use)	TP1HT 11Kv	TP1F 690V	TP5F 690V	PE80 400V	PE81 400V	PEL8 208V	
2003 THDv	2.2%	1.8%	6.1%	2.7%	2.3%	2.2%	Exact loading unknown.
2010 THDv	5.2%	2.9%	8.44%	3.26%	3.71%	2.7%	2010 11kV measurement at forward HF circuit breaker.

Table 1: Comparison of the levels of total harmonic distortion measured during sea trials and MAIB tests. (TP1HT, TP1F, TP5F, PE80, PE81 and PEL8 are names of main circuit breakers supplying specific locations in the electrical network.)

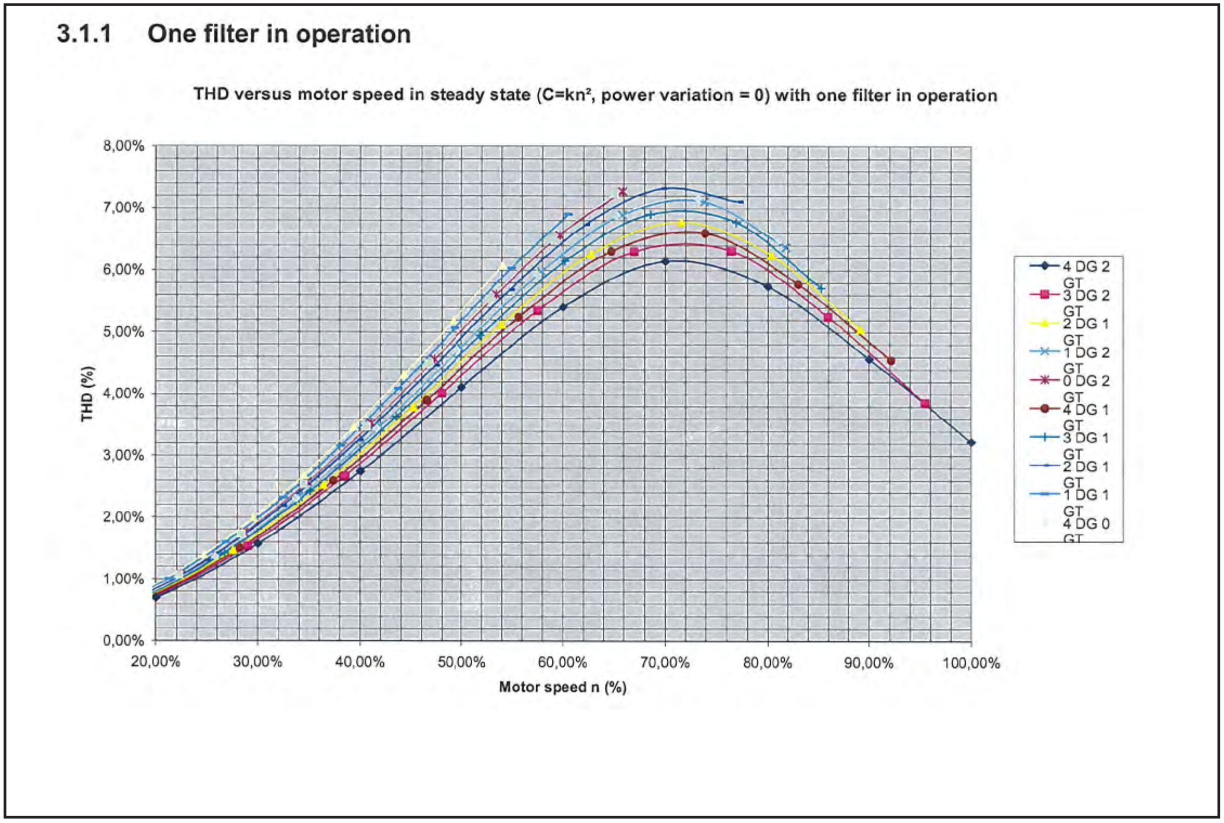
In its report of the power quality tests, Harmonic Solutions stated:

> *In conclusion, no evidence of direct or contributory factors in the failure of the aft harmonic filter capacitor(s) due to excessive voltage distortion, voltage spikes or other mains disturbances was found during the voyage.*

A month after the accident, Converteam carried out a simulated study on harmonic distortion levels expected without any HF in use. By extrapolating the graph for the case with no filters in use, the THDv was predicted to exceed 22% at 70% speed. This estimation was subsequently confirmed by Converteam when they calculated the amount of THDv in this configuration **(Figures 12a, 12b** and **Figure 13)**. In its conclusion, the Converteam study stated:

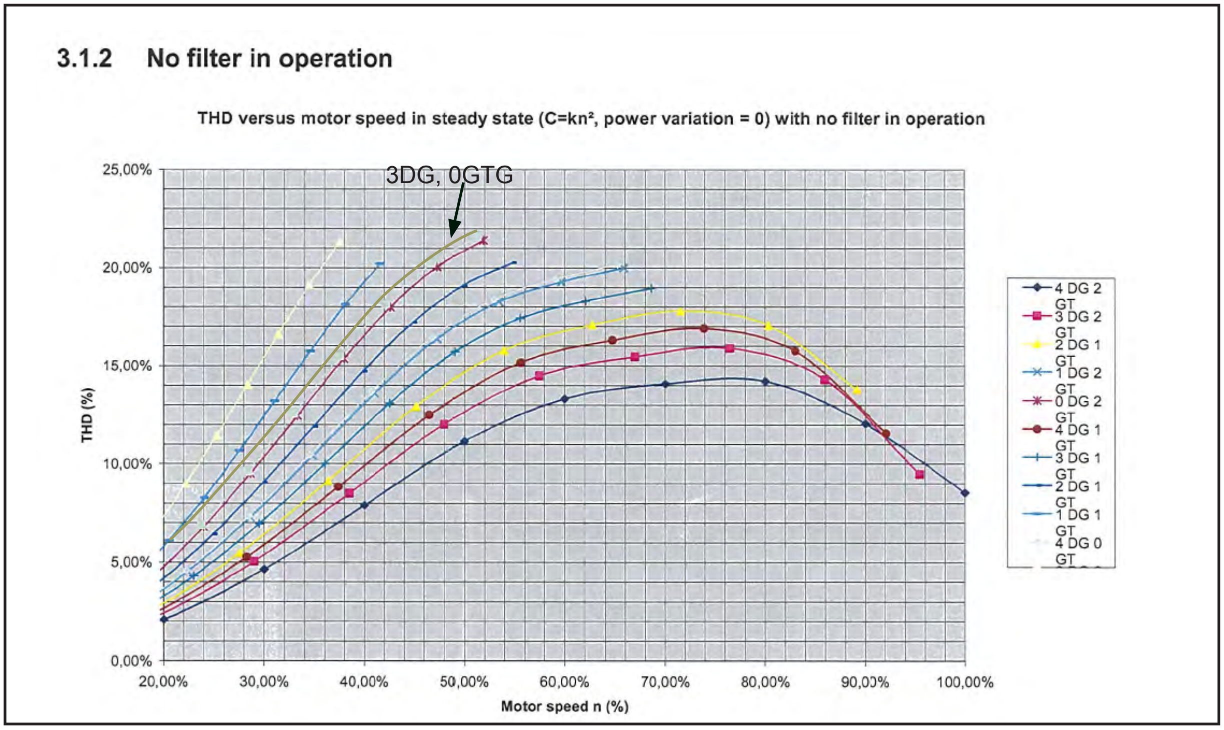
> *This study highlights the necessity to use one filter or to operate at slow speed with no filter to keep the harmonic distortion level under 8%. Additional measurements on board should be done on board to check the harmonic level with the LV [low voltage] pollution.* [sic]

Figure 12a



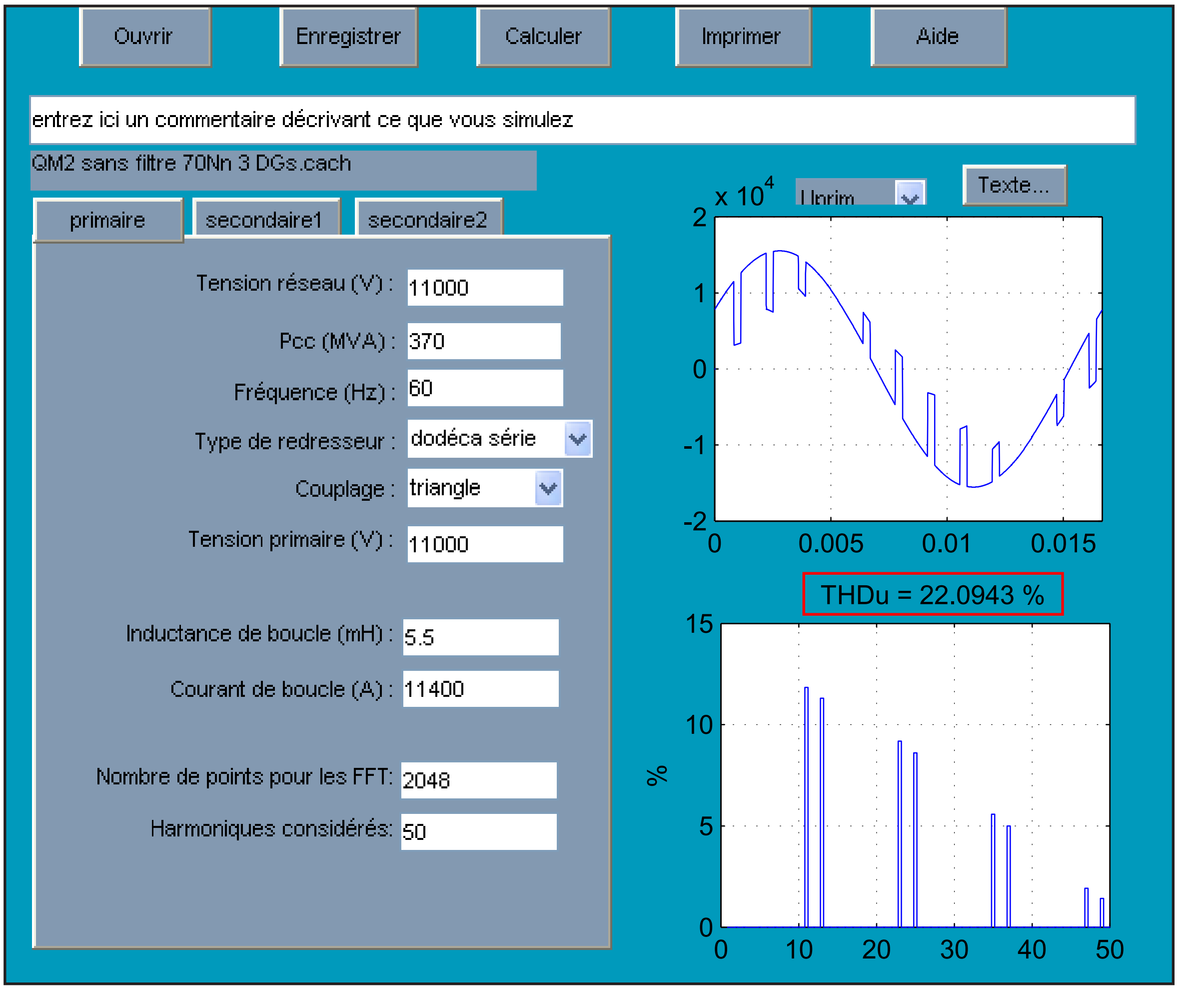
Simulation of expected total harmonic distortion of voltage with one harmonic filter in use

Figure 12b



Simulation of expected total harmonic distortion of voltage without harmonic filters

Figure 13



entrez ici un commentaire décrivant ce que vous simulez

QM2 sans filtre 70Nn 3 DGs.cach

Tension réseau (V) : 11000

Pcc (MVA) : 370

Fréquence (Hz) : 60

Type de redresseur : dodéca série

Couplage : triangle

Tension primaire (V) : 11000

Inductance de boucle (mH) : 5.5

Courant de boucle (A) : 11400

Nombre de points pour les FFT: 2048

Harmoniques considérés: 50

THDu = 22.0943 %

Simulation of expected total harmonic distortion of voltage with three diesel generators and at 70% propulsion power output

1.9 HARMONIC FILTERS

1.9.1 Harmonic mitigation

There are several methods used to counter the effects of harmonic distortion in marine power systems, including:

- active or passive filters
- increasing the number of pulses in power converters by using multiple phase shifted secondary windings in propulsion motor supply transformers
- installing generators with a large sub-transient reactance.

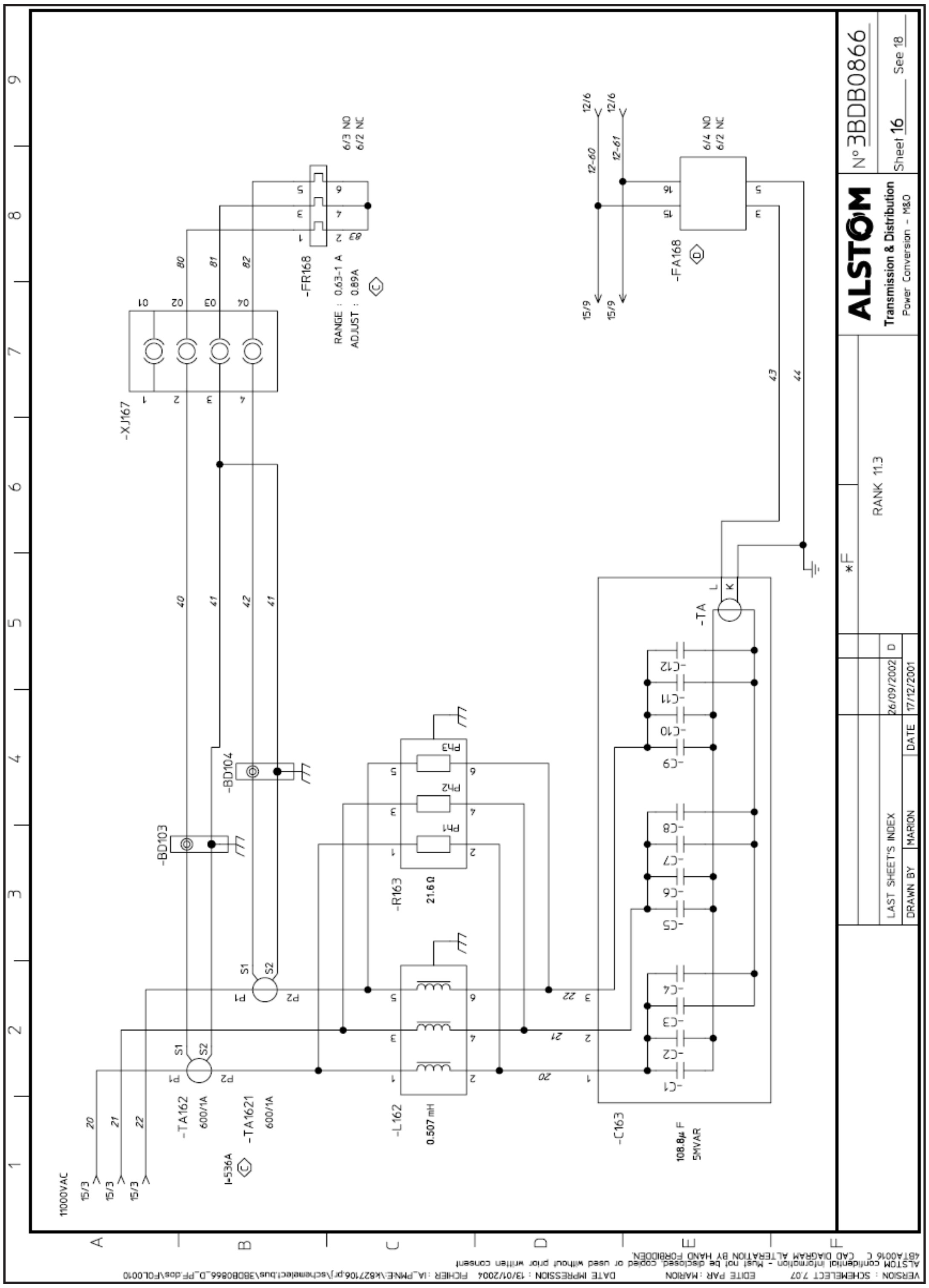
The predominant harmonics that are expected to occur in the electrical power conversion system are calculated at the design stage. The HFs in *QM2* were of the passive filter type, consisting of a tuned circuit of capacitors and inductors providing a low impedance path to the predominant harmonics, in the electrical network. The frequency to which the filter was tuned is called the resonant frequency of the system and is given by the relationship:

$f_r = 1/(2\pi(LC))$

(where f_r is resonant frequency in hertz; L is inductance in henries and C is the capacitance in farads)

The harmonic filters on *QM2* were supplied by Converteam, formerly part of Alstom Power Conversion, France. Each HF consisted of two sub-sections tuned to resonant frequencies equivalent to the 11.3rd and 4th harmonics, and referred to on board the vessel as rank 11.3 and rank 4 respectively. There were 15 capacitors in rank 4 and 12 in rank 11.3. The capacitors for each rank were connected directly to the three-phase 11kV mains supply with their terminals connected in a circuit configuration known as a double star termination **(Figure 14)**. The 11.3 rank included a group of inductors, with a total inductance of 0.507mH and a bank of capacitors with a total capacitance of 108.8μF. A resistor bank was also connected in parallel to the inductors to limit the amount of in-rush current into capacitors when the HF was started up.

Figure 14



Rank 11.3 of harmonic filters

Although the 4th harmonic is non existent in a 12 pulse converter, rank 4 was included in the HF on *QM2* to counter the excitation of lower order resonant frequencies and also to mitigate any harmonics from non-linear low voltage loads. The exact details of all the low voltage loads were not available to Converteam when the filter was being designed, and additional margins were included in rank 4 to mitigate any unexpected harmonic distortion from the low voltage network. Implementing filters at two ranks also distributed the reactive power requirement of the network across the two ranks. As the capacitors represented a large reactive component of the electrical load, the ship's crew had to ensure that the harmonic filters were always switched on after starting the propulsion motors and switched off before stopping them.

One HF could be nominated as the priority filter and the other could be set to switch in or out automatically as required. The switching-in threshold was based on the power demand of the propeller motors, and therefore while the running filter would remain on-line until it was manually switched off, the other filter would cut in and out depending on the number of generators in use and hence the power being demanded. The switching logic was designed to keep both HFs running if more than four generators were required to supply the electrical load.

The aft HF was selected as the running filter when the vessel departed Southampton on 19 September. The forward HF remained on standby and was only put on load twice, for brief periods, during 21 September. Two days after the accident, the total running hours of the forward HF was noted as 34419. The aft HF had been used for 24282 hours.

1.9.2 Acceptance tests

Factory acceptance tests for the harmonic filters were completed in July 2002 in the presence of LR. As part of these tests, the imbalance alarm and trip settings, along with their respective time delays, were verified by injecting a current into the relays connected to the secondary winding of the imbalance current transformer. Procedures for carrying out harbour acceptance tests on the harmonic filters were developed by the shipbuilding section of Carnival; but there were no installation and commissioning records available.

1.9.3 Maintenance manual and safety management system

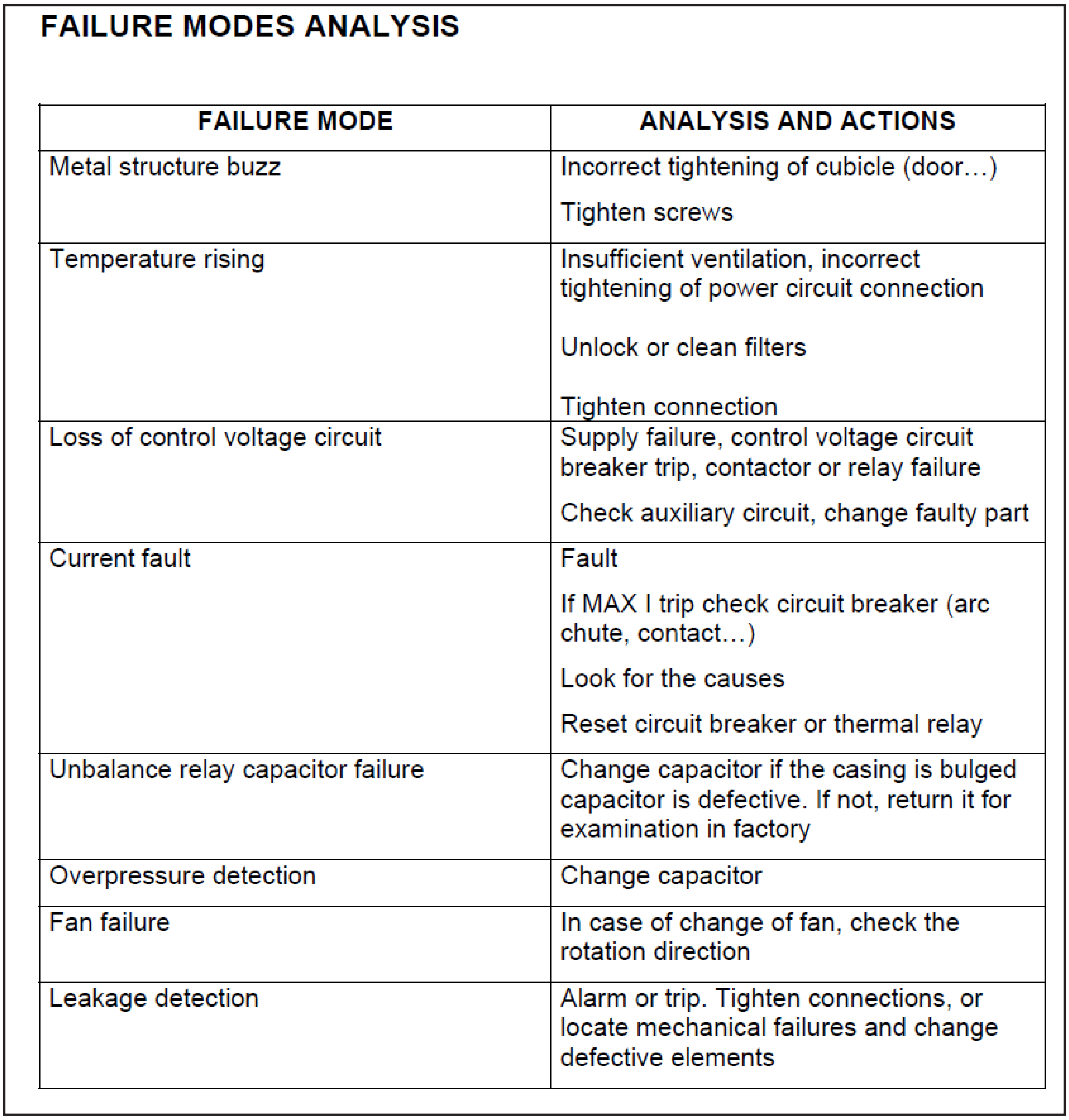
Converteam's manual for the HF contained a maintenance schedule which required the protection devices to be checked every 12 months. It did not specify how the checks were to be carried out and contained only the following:

> ***Each 12 months***
>
> *Check the protections (see main switchboards)*

The manual also contained a table entitled *Failure modes analysis* **(Figure 15)**. This analysis did not include the failure of the imbalance current protection system. It also contained a reference to overpressure detection in the HFs, a feature which was not present in the HFs on *QM2*.

The vessel's safety management system had not identified the HF as a critical piece of equipment under the definition[1] provided under section 10.3 of the ISM Code.

Figure 15



FAILURE MODES ANALYSIS

FAILURE MODE	ANALYSIS AND ACTIONS
Metal structure buzz	Incorrect tightening of cubicle (door…) Tighten screws
Temperature rising	Insufficient ventilation, incorrect tightening of power circuit connection Unlock or clean filters Tighten connection
Loss of control voltage circuit	Supply failure, control voltage circuit breaker trip, contactor or relay failure Check auxiliary circuit, change faulty part
Current fault	Fault If MAX I trip check circuit breaker (arc chute, contact…) Look for the causes Reset circuit breaker or thermal relay
Unbalance relay capacitor failure	Change capacitor if the casing is bulged capacitor is defective. If not, return it for examination in factory
Overpressure detection	Change capacitor
Fan failure	In case of change of fan, check the rotation direction
Leakage detection	Alarm or trip. Tighten connections, or locate mechanical failures and change defective elements

Failure modes analysis section in manufacturer's maintenance manual for harmonic filters

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[1] *The Company should identify equipment and technical systems the sudden operational failure of which may result in hazardous situations.*

1.10 CAPACITORS

1.10.1 Design, construction and manufacturing

The capacitors were manufactured by Vishay Electronic (Vishay) at Blatna in the Czech Republic. Each capacitor can[2] measured approximately 93 x 35 x 18cm and consisted of 36 individual elements **(Figures 16a, b, c** and **d)**. An individual element had a capacitance of approximately 12μF and a group of nine such elements connected in parallel had a capacitance of 108.8μF. Four such groups of nine were connected in series achieving a total capacitance of 27.2μF for each can[3]. The capacitor elements were made up of two aluminium foils separated by an insulating polypropylene layer. The entire assembly was wrapped in insulating paper and immersed in dielectric oil Jarylec C101, which filled the can **(Annex B)**; the oil and the polypropylene made up the dielectric medium for the capacitor. The capacitor assembly was rated at 8242V. It was not fitted with any internal fuses, pressure monitoring or relief devices.

The construction and testing standards that were used by Vishay were:

- IEC 60871-1 Shunt capacitors for AC power systems having a rated voltage above 1000V – Part 1: General; and,
- IEC 60871-2 Shunt capacitors for AC power systems having a rated voltage above 1000V – Part 2: Endurance testing.

Under normal operating conditions, Vishay estimated that each capacitor should have a working life of around 20 years.

The temperature rating of the capacitors was '-15 B'[4] which meant that the minimum temperature at which the capacitor could operate satisfactorily was -15ºC; B indicated that the maximum ambient operating temperature was limited to 45ºC, with the highest mean over any period of 24h being 35ºC. In December 2010, while the vessel was in Caribbean waters, surface temperature measurements, using wax-filled stickers, were carried out on capacitors in both ranks of the forward HF. The maximum recorded surface temperature was 49ºC on a rank 4 capacitor and 46ºC on rank 11.3. A measurement of the temperature on a capacitor in rank 11.3 in the same position as the one which failed on 23 September, was recorded as less than 44ºC, which was the minimum the wax-based sensor was capable of measuring. The high temperature alarm for cooling air inside the HF enclosure was set at 47ºC with a '*high High*' alarm setting of 50ºC. The maximum temperature of the air in the forward HF during the test period was measured at 36ºC.

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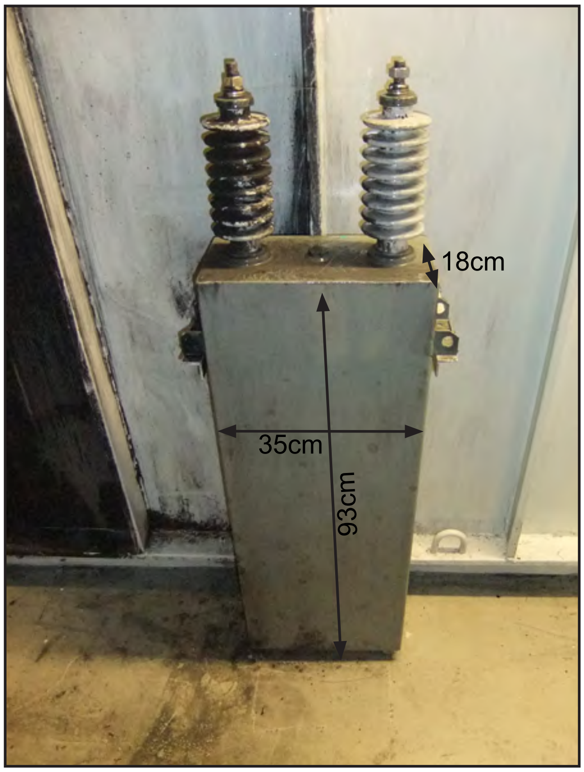
[2] Can – the term used to describe the external casing of a capacitor.

[3] When capacitors are connected in parallel, the total capacitance of the group is given by the relationship $C = c_1+c_2+ \ldots + c_n$ where $c_1 \ldots c_n$ are capacitances of individual capacitors and C is the combined capacitance. When connected in series the relationship is
$1/C = 1/c_1+1/c_2+ \ldots + 1/ c_n$

[4] In accordance with IEC 60871-1 clause 4.1 c

Figure 16a

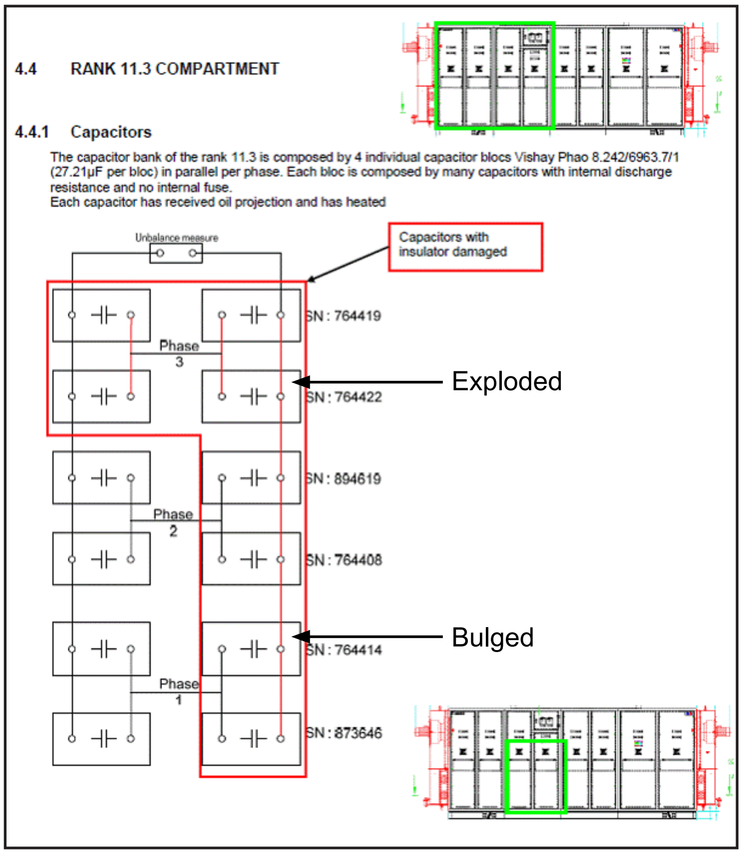


Capacitor used in harmonic filters

Figure 16b

Internal elements

Figure 16c



4.4 RANK 11.3 COMPARTMENT

4.4.1 Capacitors

The capacitor bank of the rank 11.3 is composed by 4 individual capacitor blocs Vishay Phao 8.242/6963.7/1 (27.21µF per bloc) in parallel per phase. Each bloc is composed by many capacitors with internal discharge resistance and no internal fuse.
Each capacitor has received oil projection and has heated

Block diagram

Figure 16d

Single capacitor element

IEC 60871-1 states that when inductive elements are included in series with capacitors to mitigate the effects of harmonics, the voltage at the capacitor terminals would exceed the expected voltage at the capacitor. Therefore, such capacitors should be rated to withstand the increased voltage. Converteam's specification to Vishay for the capacitors did not mention this factor specifically, but achieved a similar effect by requiring the rated voltage of the capacitors to be an amount equal to the sum of the fundamental voltage at the capacitor bank and all the harmonic voltages up to the 30th harmonic order.

The capacitor manufacturing process was not subject to any LR approval procedures, and the society's rules at the time did not have any rules regarding the construction or fitting of capacitors. There were no requirements in LR's rules for capacitors to be fitted with protection or monitoring devices and Converteam did not include any in its specification. However, Vishay provided the current imbalance detection system as standard.

Shortly after the accident, Converteam's supplier quality assurance department carried out an audit of Vishay's construction process against IEC 60871-1. No deficiencies in the capacitor design and construction process were recorded.

1.10.2 Test of failed capacitors by Vishay

All the capacitors from Rank 11.3 that were in use at the time of the accident, including the exploded and bulged ones, were returned to Vishay's Blatna facility. Both the failed and bulged capacitor elements were examined by Vishay staff. In their subsequent report, they identified that the two most common reasons for severe reduction in capacitor life, were exposure to frequent transient voltages and increased operating temperatures. Vishay was unable to form any conclusions as to the cause for failure due to the severe disintegration and fusing together of the elements in the exploded capacitor. Vishay concluded from its examination of the bulged capacitor and its elements, that the defects observed on the elements must have occurred over a longer period of time. In trying to establish the probable cause of failure, the report stated:

> *'Another theory could be a defect on parts of the safety circuit, the failing of an element in a capacitor cannot be recognized. Due to the increased voltage on the sound groups flashover will happen in these groups after some time of operation. So this capacitor will end with a shortage.'* [sic]

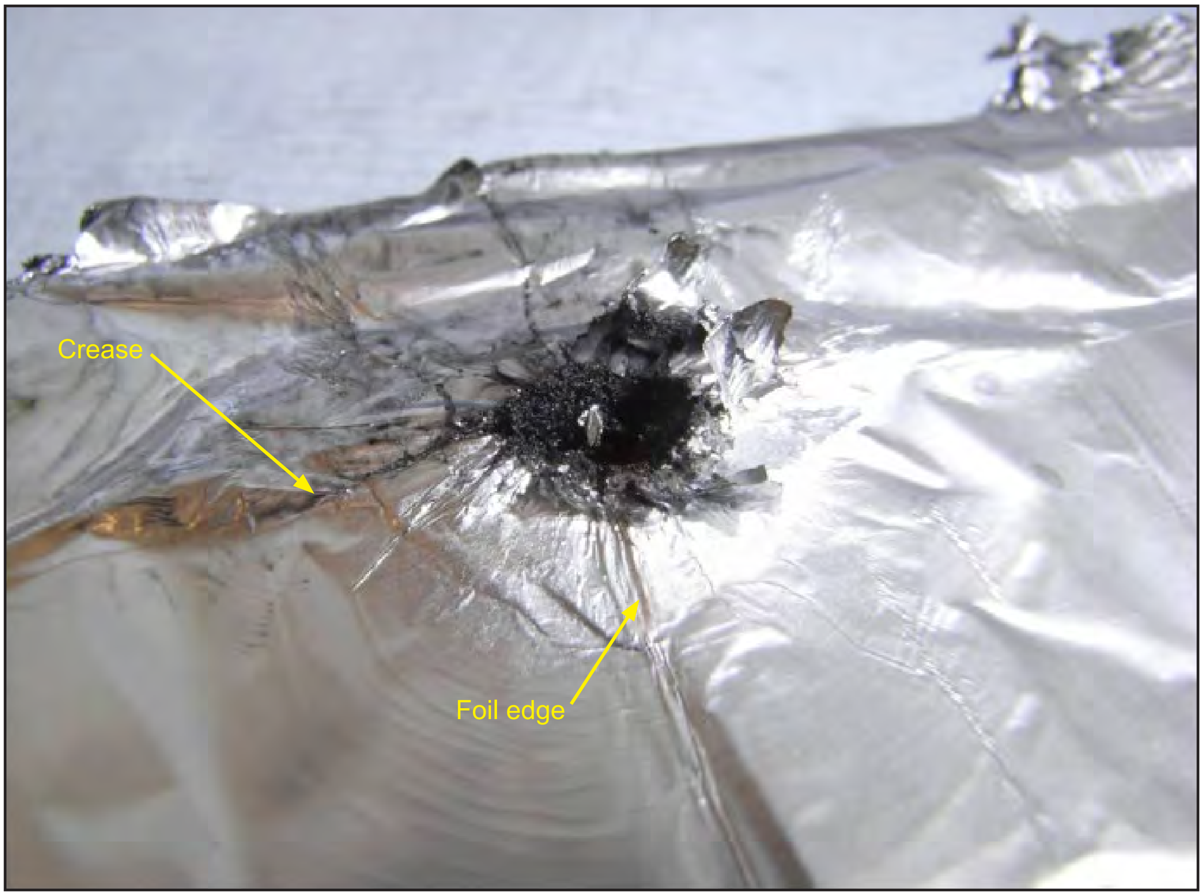
The report went on to state that if a defective capacitor went undetected by a failed safety circuit, it would suffer from internal heating as it drew current, resulting in the polypropylene film swelling up and eventually ripping off the contacts on the elements. This would cause an electric arc to develop at the broken connections, which in turn would cause the dielectric oil to vaporise, increasing the internal pressure and, ultimately, the catastrophic failure of the capacitor. The report of Vishay's examination is at **Annex C**.

1.10.3 Test of failed capacitors commissioned by MAIB

The MAIB commissioned ERA Technology Ltd to carry out an independent examination of the two damaged capacitors and one intact capacitor from Rank 11.3. Its major findings were as follows:

- *Excessive currents leave characteristic signs of overheating damage. No such signs were observed in any of the elements inspected.*
- *When a capacitive element fails, it almost inevitably fails short circuit.*
- *One of the roots of an element failure was traced to the junction of the edge of the foil and a crease in the electrode film. Such creases are natural stress raisers and should be avoided as much as is practical* **(Figure 17)**.
- *The fact that the unit did fail catastrophically indicates that either there was a system side problem overstressing the capacitor or that the capacitive elements could not perform to their stated rating.* [sic]

Figure 17



Crease on capacitor element

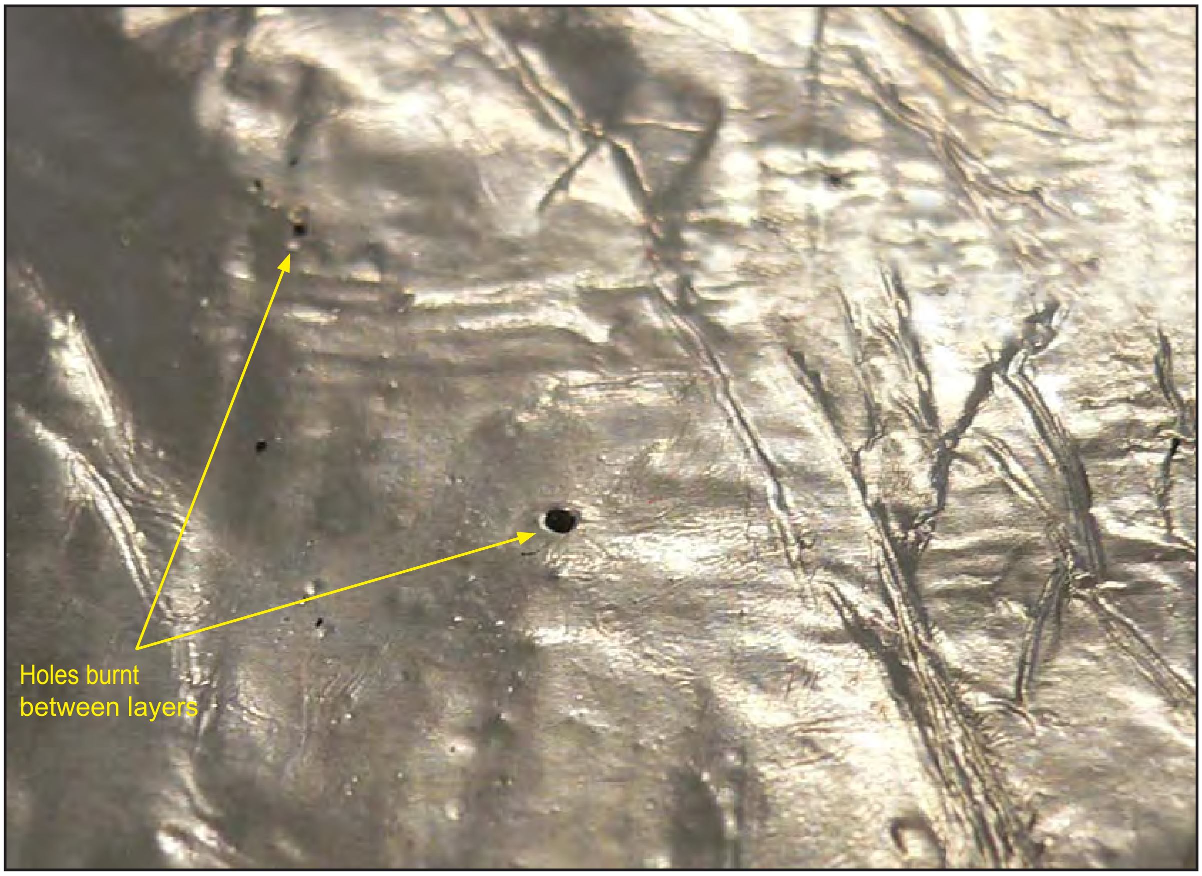
An element from the bulged capacitor was inspected and very small round holes, the largest of which was approximately 0.5mm diameter, were found between two layers **(Figure 18)**. With reference to these holes, the report stated:

> *'This type of damage is typically associated with transient overvoltage. However, it is not possible to say, from the physical evidence whether or not the transient over voltage was generated by disturbances [in the supply] or as a result of the prior failure of other elements in the capacitor.'*

The report concluded:

> *'… it is probable that the incident was initiated by the failure of a single capacitor element and that the failure initiated the progressive failure of the whole unit …'*

Figure 18



Holes in capacitor element from bulged capacitor

1.10.4 Overvoltage in the electrical network

In the first year of service, *QM2* had several issues related to overvoltages in the electrical network. Voltage fluctuation was recorded ten times in one particular day, with the highest voltage level reaching 13.4kV, nearly 22% more than the rated voltage. On 9 September 2010, both anchor windlass motor drives were damaged due to overvoltage in the supply from the main switchboard. The vessel also blacked out during this event.

IEC 60871-1 states that a capacitor would experience the maximum overvoltage when it is switched on. The first peak of this transient overvoltage is expected to be as high as $2\sqrt{2}$ times the applied RMS value of the voltage, for a maximum duration of half a cycle. The standard also requires that the capacitor be capable of 1000 switching operations in a year.

LR's rules allow permanent variation of voltage up to +6% and -10% in the electrical network. Transient variations of up to 20% of the rated supply voltage, with a recovery time of 1.5s are also permitted.

1.10.5 Dielectric oil test

Six days after the accident, approximately 30ml of dielectric oil was collected from the deck of the aft HF enclosure. For comparison, a further 190ml was collected from a sealed capacitor when it was opened up for examination by ERA Technology. The samples were analysed by a specialist laboratory, Nynas Naphthenics, and its findings are summarised as follows:

- Thermal degradation, or ageing of Jarylec C101 and paper insulation leads to the formation of gases.

- Localised overheating can cause the gas formation to become capable of carrying a charge. This process can accelerate in the resultant electric field causing further ionization. Due to the self-healing properties of the oil, the ionisation process is sometimes halted, thus preventing further damage. However, solids such as polypropylene and paper which make up the insulation in the dielectric medium do not have self-healing properties.

- Moisture concentration in both oil samples (from exposed and sealed capacitors) was found to be well above the typical values (40 mg/g) reported by the supplier of dielectric fluid. As the moisture increases, voltage breakdown thresholds are lowered.

- Further water molecules are produced when paper degrades, increasing the overall moisture content.

- Although the flash point of Jarlylec C101 is normally 144^{o}C, the gases formed during the breakdown of the liquid and solid parts of the dielectric medium lower the overall flashpoint, making the mixture flammable at room temperature.

- Acetylene was present in the oil sample from the exploded capacitor, indicating a high probability of internal arcing through the dielectric medium.

The report stated:

> *The generation of gases during a partial discharge, sparking or arcing, is very rapid and if the system is a closed system, the high pressures generated may compromise the containment by rupturing or even exploding. Further those gases have a high content of hydrogen and light hydrocarbon gases which themselves are flammable and explosive in the presence of oxygen or air.*

1.10.6 Supply and returns history

The first recorded failure of a capacitor on *QM2* was in January 2006. Since then, Vishay has supplied 11 replacement capacitors to the vessel: 2 for rank 4 and 9 for rank 11.3; no spares were supplied at delivery in 2003. Seven capacitors were returned from the vessel to Vishay, of which one was found to have a defective internal element, five had sustained mechanical damage and one had an overheated contact. At the time of the accident there was one spare capacitor on board, which was for rank 4.

1.10.7 Maintenance and failure history

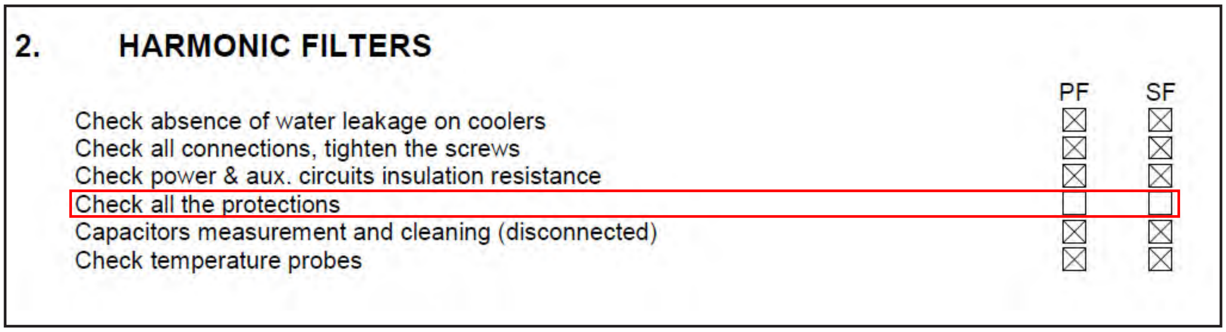
While the vessel was in service, capacitor replacement was generally triggered by an imbalance alarm or as the result of a visual inspection identifying that the casing had bulged or dielectric fluid was leaking. The usual practice upon receiving an imbalance alarm was for the duty engineer to alert the chief electrical officer, who would then visit the appropriate HF compartment and carry out a visual examination and check for any smell of dielectric oil. If the cause could not be established by visual examination, the crew would isolate the HF concerned and identify the capacitor that had caused the alarm by disconnecting the capacitors in each phase and measuring the total capacitance. Once the defective phase had been identified, each capacitor in that phase would be disconnected and measured individually until the failed unit was found. It was difficult to gain access to each capacitor and the crew would often have to shift all the capacitors along the foundation rails and insert the replacement one at the end. The serial numbers of damaged capacitors were not recorded.

A total of five capacitors were replaced in the forward HF. Of these, it was recorded that three were from rank 11.3; but it was not known which rank the other two capacitors came from. When the failures first began to occur in early 2006, crew had to take capacitors from the aft HF to use in the forward HF as the only spare one on board was damaged during fitting. The vessel then operated without the aft HF for several weeks until the spare capacitors were delivered.

Six capacitors were replaced in the aft HF, with the first one failing in rank 4 during July 2006. The remaining five were all from rank 11.3. The maintenance management system did not record the reasons why these capacitors were replaced. However, of the five capacitors replaced in rank 11.3 of the aft HF, it was later found that four were changed after routine checks conducted during dry docking periods. During the dry docking period in 2006 Converteam, working with Vishay, replaced two capacitors in rank 11.3 of the aft HF. One was found to be leaking and the other had bent connections. The capacitance values of the damaged capacitors were not recorded and they were not returned to Vishay for further analysis.

Converteam checked all the capacitors in both harmonic filters in October 2008 while the vessel was in dry dock. Two capacitors were found to be defective, with capacitance readings of 36.8μF and 36.9μF. These readings should have activated the imbalance alarm, but the corresponding alarm was not triggered. Converteam reported its findings about the failed capacitors to Carnival in a document which summarised all of the many tasks that had been carried out in dry dock. The document **(Figure 19)** also indicated that the imbalance detection system had not been tested.

Figure 19



2. HARMONIC FILTERS

	PF	SF
Check absence of water leakage on coolers	☒	☒
Check all connections, tighten the screws	☒	☒
Check power & aux. circuits insulation resistance	☒	☒
Check all the protections	☐	☐
Capacitors measurement and cleaning (disconnected)	☒	☒
Check temperature probes	☒	☒

Extract from Converteam's dry dock attendance report to Carnival UK in 2008

1.10.8 Classification society survey records

The aft HF was last surveyed in November 2006 and the forward HF in July 2010 under the 5-yearly cycle of continuous survey of machinery (CSM). The CSM survey consisted of a visual examination of the harmonic filters while the vessel was in port. Imbalance alarms and trips were not tested.

Although the capacitors were in sealed cans, the survey listed a requirement for a '*Converter and harmonic filter insulation fluid test'*. The capacitors were credited as passing this test in both surveys, despite it being impossible to withdraw fluid without damaging the casing.

1.10.9 Polypropylene vapour

In 2007, the classification society Det Norske Veritas AS (DNV) sent a circular aimed at '*manufacturers of frequency convertors for propulsion and thrusters'* **(Annex D)**. In this circular DNV raised the issue of flammable gases being released from polypropylene film used in capacitors. The circular stated:

> *Recent knowledge has shown that there is a risk that the film material may release flammable gases to the environment because of overheating or melting. In enclosed cubicles these gases may lead to a hazardous environment that can ignite and cause explosion. Resent experience shows that this may cause danger to personnel and risk for damage to equipment located in the vicinity [sic].*

1.10.10 Improvements made to capacitor design

During the course of this investigation, all the capacitors in the aft HF on board *QM2* were replaced. A number of changes to the design of the capacitors were made by Vishay, which improved the robustness of the capacitors. Voltage of each element was reduced by 20% and by using a different grade of polypropylene film the electrical stress was reduced by 5%. Each capacitor element was individually fused and pressure sensors were fitted to detect internal overpressurisation.

1.11 CURRENT IMBALANCE DETECTION SYSTEM

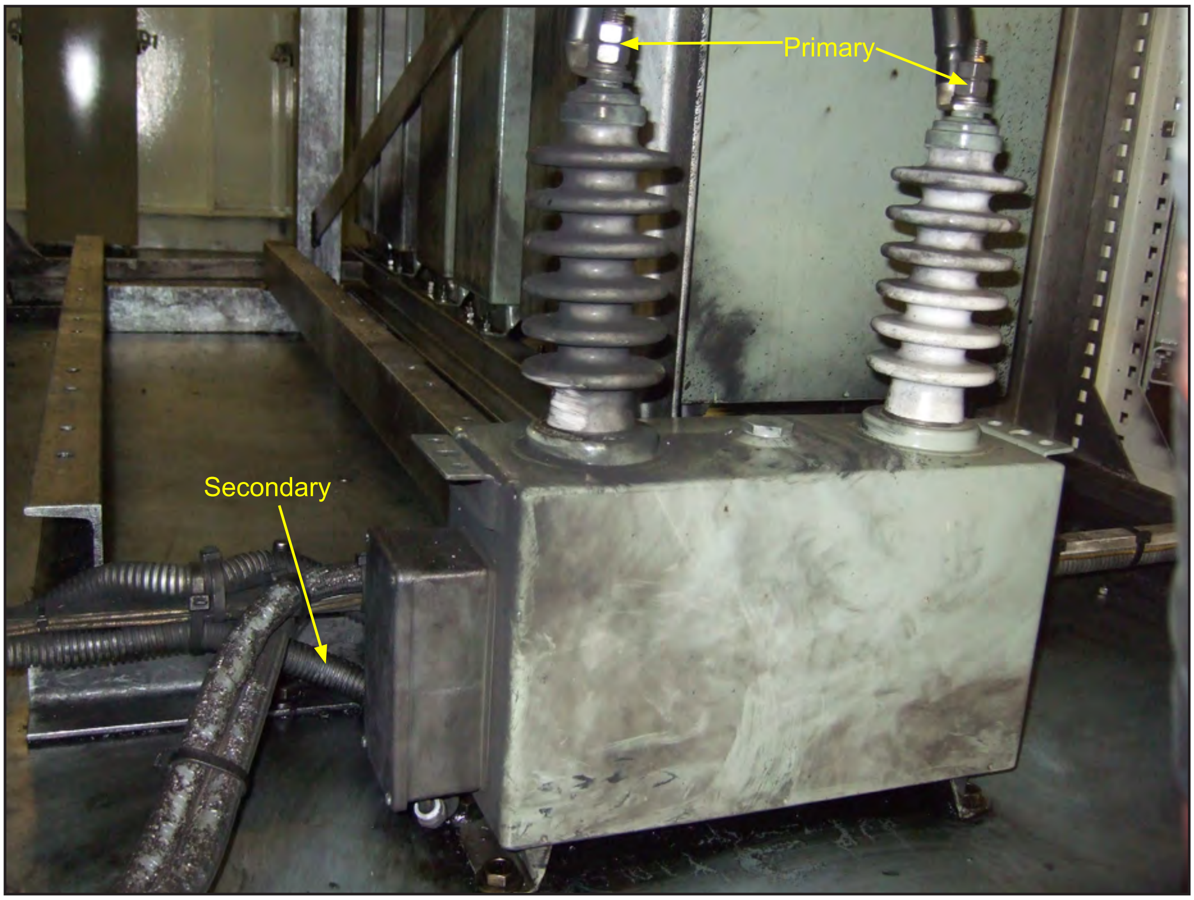
1.11.1 Construction

The two neutral points at the double star termination of the capacitor circuit were connected to the primary coil of a current transformer **(Figure 20)** which had a current ratio 10:1 (50A at the primary winding and 5A at the secondary winding) and was part of the monitoring and protection system *'EstaSym 3C'* supplied by Vishay Electronics GmbH, Germany. There were no records available to verify the transformer's service history.

The secondary winding of the transformer was connected to a current imbalance detection relay unit with a display fitted on the panel of the HF enclosure. The current imbalance detection system worked on the principle that when all the capacitors were in good order, the two neutral points of the double star termination would be at a similar potential. Consequently, there would be very little current flowing across the primary winding of the transformer and therefore very little induced secondary current would be recorded on the display. If a capacitor degraded, the change in the overall capacitance would unbalance the system and cause a current to flow through the transformer. An imbalance alarm would be triggered if this current exceeded 400mA, and at or above 800mA the main circuit breaker of the HF would trip, isolating the HF from the electrical network. A full short circuit in one group of elements in the capacitor was calculated to develop an unbalanced current of 1300mA. Both alarm and trip relays had a time delay of 300ms to reduce the number of spurious alarms or trips due to transient effects.

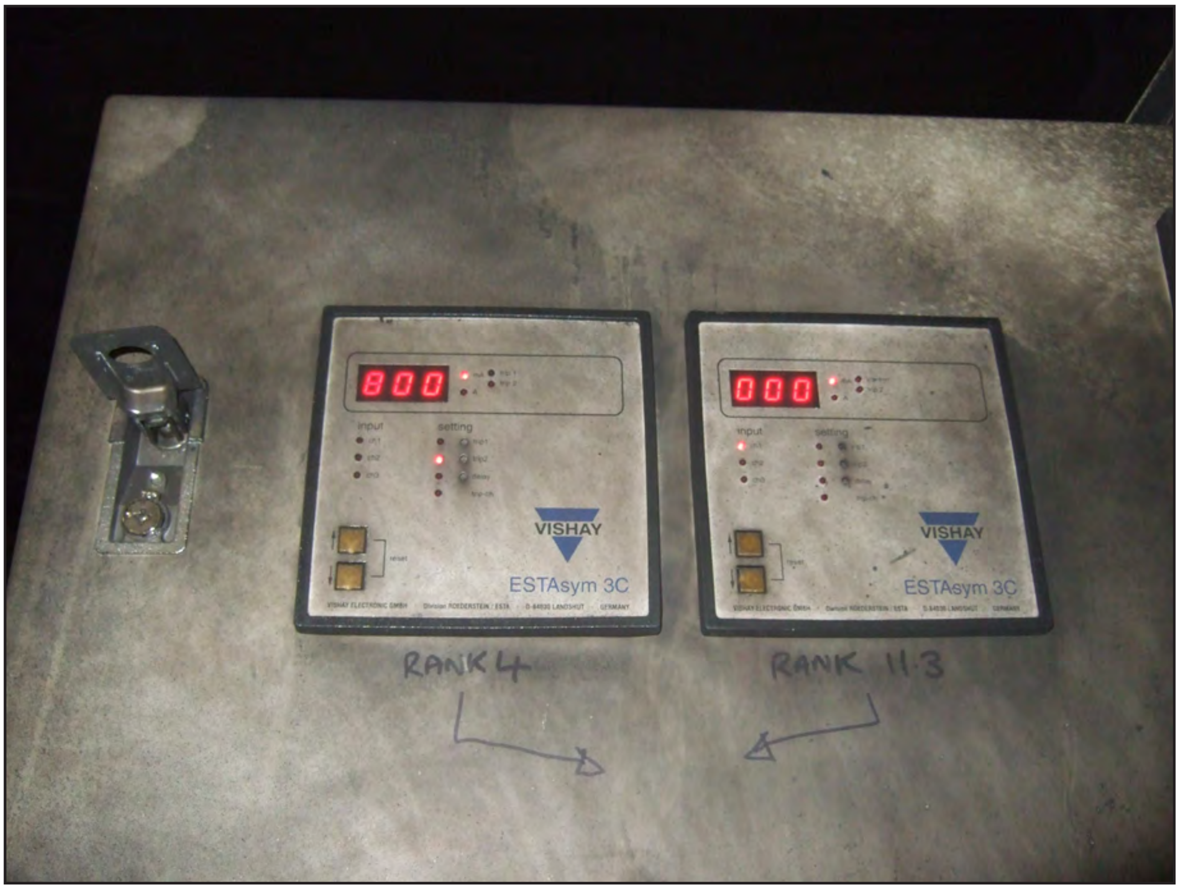
Immediately after the accident, the imbalance detection unit for rank 4 of the aft HF indicated 800mA and the equivalent unit on rank 11.3 (where the failure took place) showed '000' **(Figure 21)**. Cooling water leakage and cooling air alarms were also provided for each rank. These alarms did not activate during the accident. An overload alarm was also provided but it was not possible to determine from the alarm records if this activated during the accident.

Figure 20



Current transformer for the imbalance detection system

Figure 21



Current imbalance indicators in the aft harmonic filter room

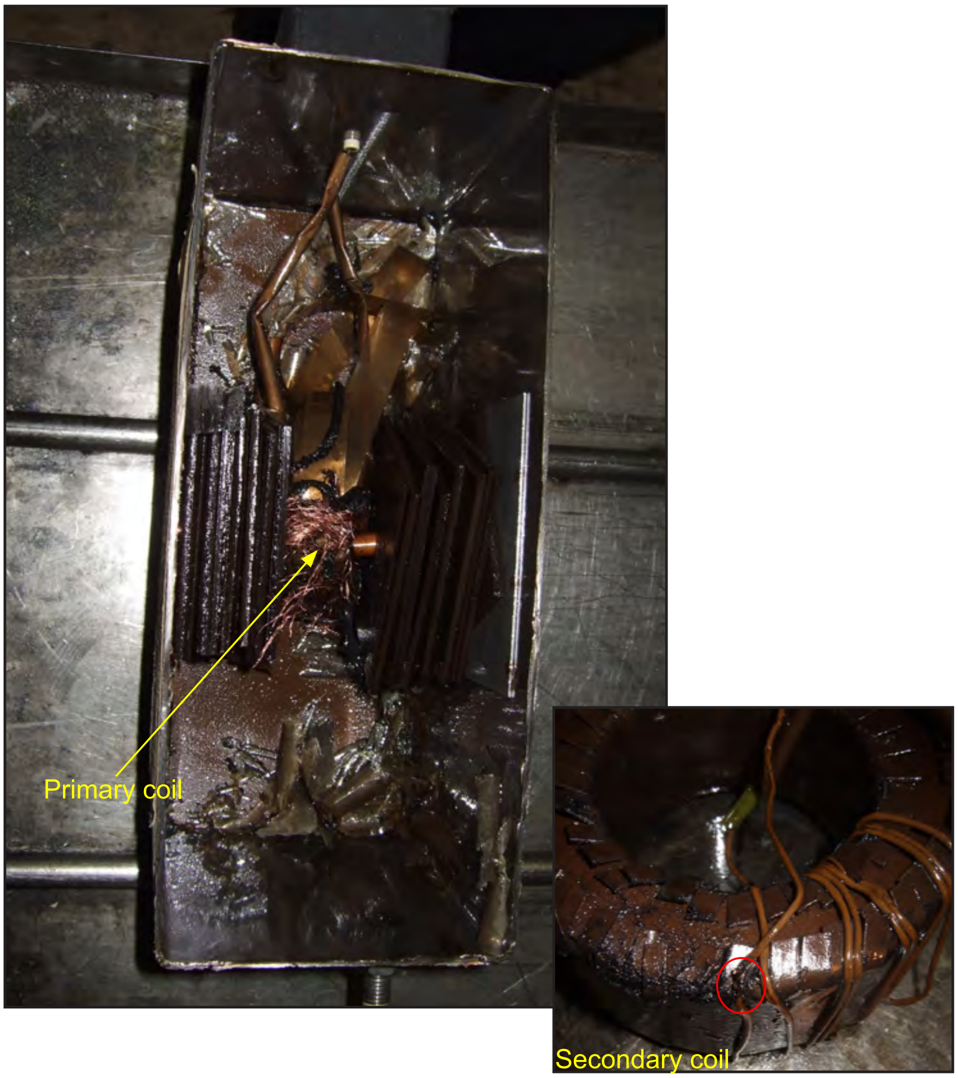
1.11.2 Test by Converteam

In January 2011 the protection system for Rank 11.3 was tested by Converteam and witnessed by MAIB inspectors. Current was injected directly into the relays to simulate imbalance currents. They were found to be functioning correctly and settings were verified as being 400mA for the alarm and 800mA for the trip functions. The protection transformer windings were then checked for electrical continuity, and both the primary and secondary windings were found to have failed in open circuit. The transformer, which was a sealed unit, was sent to Vishay for an intrusive examination.

1.11.3 Examination by Vishay

The casing of the imbalance current transformer was cut open by Vishay and witnessed by representatives from MAIB and Converteam. The transformer oil was very dark in appearance and contained visible solid debris. The primary winding was found severely damaged, with most of its insulation missing. The copper wire in the secondary winding was broken at one place and held together by damaged insulation. The wire had flattened and insulation broken where it had been wound around the edges of the transformer's iron core **(Figure 22)**. The complete report is at **Annex E**.

Figure 22



Current transformer for the imbalance detection system with its casing cut open (inset: secondary coil)

1.11.4 International standard for current transformers

IEC 60044-1 Instrument transformers – Part 1: Current transformers, states *Current transformers intended for both measurement and protection shall comply with all the clauses of this standard.* The standard defines in detail several requirements covering the areas of design, testing, accuracy and insulation. The current transformer used in the EstaSym 3C protection system for harmonic filters on *QM2* was built in-house by Vishay and was not intended to meet any specific standard.

The standard stated:

> *Current transformers should not be operated with the secondary winding open-circuited because of the potentially dangerous overvoltages and overheating which can occur.*

In February 2011, at the MAIB's request, Converteam carried out a verification audit of Vishay's manufacturing process for the current imbalance transformer against IEC 60044-1, even though construction to this standard was not in the scope of the original requirement presented by Converteam to Vishay. Of the 23 requirements that were checked, 15 did not comply with the standard. Some of the most significant items which did not comply were:

5.1.4	*Insulation requirement for secondary windings*
5.1.5	*Inter-turn insulation requirement*
8.4	*Inter-turn overvoltage test*

Converteam also carried out an analysis of initial sub-component inspections that were carried out by Vishay during the manufacture of the current imbalance transformers for *QM2*. Five transformer sub-components were identified and the checks that were carried out included visual inspection, mechanical checks, electrical tests, chemical analysis and verification of product data from the component supplier. Post production electrical tests were successfully carried out on both windings.

However, despite these shortcomings, Converteam's conformity checks summarised:

> *In conclusion, we can say that process, inspection and test done by VISHAY is suffisant compared to the use and function of this current transformer* [sic].

1.11.5 Monitoring and protection

The SOLAS[5] regulation regarding the monitoring and protection of machinery states:

> *'Where main or auxiliary machinery including pressure vessels or any parts of such machinery are subject to internal pressure and may be subject to dangerous overpressure, means shall be provided where practicable to protect against such excessive pressure.'*

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[5] SOLAS consolidated edition 2009, Chapter II-1, Part C Regulation 27.2

A technical brochure published by Vishay ‘Mounting and Maintenance Instructions, Static Power Capacitors, Naturally Air-Cooled’ **(Annex F)** stated:

> ***Explosion or Fire hazard:***
> *Even if monitoring and safety devices exist, the incidence of overloading or an important electrical defect may cause the destruction of the casing and/or the bushings. Another consequence of this may be that the capacitor’s combustible component parts catch fire. This aspect shall be taken into account at the site of erection of the capacitor.*

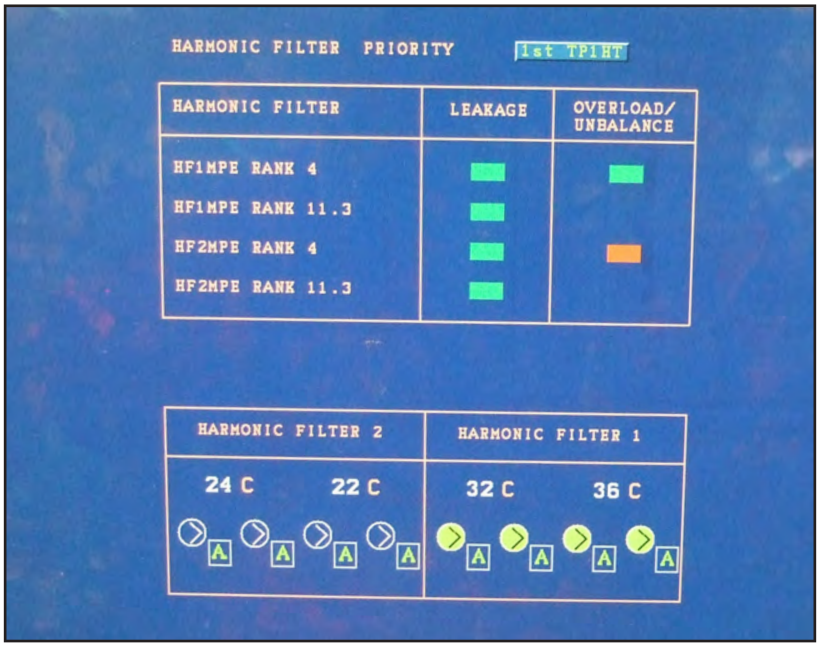
In a technical paper published by The Institute of Marine Engineers in 1995 titled ‘Electric propulsion – a view from a classification society’[6], the authors in a discussion on harmonic filters stated:

> *‘With regard to filters, it is perhaps worth noting that overpressure in capacitors cans may have to be included in the protection arrangements…’*

While the authors discussed this matter in the paper, there was no specific regulation or classification society rule that required such protection of capacitors in high voltage equipment. The general requirement in SOLAS was not interpreted as being applicable to the capacitors.

When the IAS received an imbalance or overload alarm from an HF, the duty engineer could interrogate the graphical user interface (GUI) in the ECR, which indicated the rank of the HF which was in alarm **(Figure 23)**. The GUI display for both the overload and the imbalance alarm was combined, and read ‘OVERLOAD/ UNBALANCE’. If the circuit breaker to the HF was tripped, it would be indicated as an additional alarm in the IAS, as an electrical fault on the breaker. There were no records of the imbalance alarms or trips being tested either at commissioning, or at any other point in the life of the vessel.

Figure 23



HARMONIC FILTER PRIORITY 1st TP1HT

HARMONIC FILTER	LEAKAGE	OVERLOAD/ UNBALANCE
HF1MPE RANK 4	🟩	🟩
HF1MPE RANK 11.3	🟩	
HF2MPE RANK 4	🟩	🟧
HF2MPE RANK 11.3	🟩	

HARMONIC FILTER 2		HARMONIC FILTER 1	
24 C	22 C	32 C	36 C

Engine control room display of harmonic filter operating parameters

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[6] J. B. Borman and B.P. Sharman Electric propulsion – a view from a classification society. In *Electric Propulsion: The Effective Solution*, The Institute of Marine Engineering, October 1995

The imbalance protection relays were set to alarm at 400mA and trip at 800mA. The value of any imbalance current that exceeded these settings was shown on the display until manually reset. Staff at Vishay considered it to be extremely unlikely that the display would indicate 000mA in normal service as it would indicate that all the capacitors had exactly the same performance. The instruction manual did not mention this point.

1.11.6 History of imbalance alarms

There was no evidence to indicate that the HF breakers had ever tripped due to imbalance currents in *QM2*'s service history. The imbalance alarm currents displayed on the EstaSym displays were not usually recorded, except on rare occasions when the ship's crew discussed these issues with Converteam. A historical analysis (from 2004 to 2010) of harmonic filter overload/imbalance alarms revealed that the aft HF alarm had been triggered on nine separate occasions. The IAS system did not display or store information on which rank of the filter had registered an alarm condition.

Other records showed that an alarm, indicating problems with rank 4 of the aft HF, occurred in July 2006 while the vessel was en-route to New York. The ship's staff isolated the HF, carried out a visual examination and, finding nothing untoward they switched it back on-line. After arriving at New York, they measured the capacitance of each individual capacitor in the rank. They found that one of them measured 38.9µF, indicating that a group of nine elements had stopped working due to the failure of one or more elements in that group.

In December 2010, while the vessel was sailing at normal service speed, the alarm for rank 4 of the forward HF activated. On inspection, the imbalance current was 1250mA. Although well in excess of the trip setting of 800mA, the HF did not trip due to a wiring fault in the protection system. The crew stopped the propulsion motors, switched off the circuit breaker for the harmonic filter and increased the speed back up to 50rpm while monitoring the THDv using a portable instrument that was held on board. In this way they were able to restore limited propulsion power while maintaining an acceptable THDv of 6.2%. They subsequently replaced a capacitor in rank 4 whose capacitance measured 38.4µF. The vessel was then brought back up to full speed. The imbalance reading of rank 4 returned to 120mA. The imbalance current in rank 11.3 remained at 65mA throughout the incident.

1.12 ARC-FLASH

1.12.1 Phenomenon of arc-flash

When an electric current flows through air gaps between conductors, an arc-flash is said to occur. An arc can form between phase-to-ground (or neutral), or phase-to-phase, and is accompanied by ionisation of the surrounding air. When the air quality is degraded with moisture or other impurities, the possibility of an arc striking is increased. The arc column temperature can vary from 5000K to 20,000K and the intense heat can vaporise the conductors and surrounding materials. Copper in solid form sublimates to 64,000 times its volume, causing further deterioration of the air's insulation quality; a phase-to-phase or phase-to-ground arcing fault can escalate into a three-phase arcing fault in less than 1/1000 of a second. The heat of the arc column also heats up the surrounding air, which then moves into the surrounding cooler air with a speed exceeding that of sound, causing a shock wave and explosive noise.

An arc-flash is not normally established below a phase-to-phase voltage of 208V or phase-to-ground voltage of 120V. At higher voltages, it can cause severe shock waves, splattering of molten debris, loud explosions due to the rapidly released vapour as well as serious burn injury to anyone in the vicinity. The arc has a tendency to move away from its source.

The Maritime and Coastguard Agency's (MCA) Code of Safe Working Practices for Merchant Seamen (COSWP) contains some guidance on working with high voltages and discusses the appropriate use of permit and sanction to work. It does not contain any advice on control measures to mitigate the hazards of arc-flash.

1.12.2 High voltage regulations for enclosures

LR's rules on switchgear and control gear assemblies were only applied to the main switchboards on *QM2* and were not applicable to the HF enclosures. Under section *7.16.5.*, LR's rules state:

> *For switchgear and control gear assemblies, for rated voltages above 1 kV, arrangements are to be made to protect personnel in the event of gases or vapours escaping under pressure as the result of arcing due to an internal fault. Where personnel may be in the vicinity of the equipment when it is energised, this may be achieved by an assembly that has been tested in accordance with Annex A of IEC 62271-200 and qualified for classification IAC (internal arc classification)*

The main switchboard enclosures were supplied by ABB and were the Unigear C/G12 type. The construction consisted of an extra chamber above the main circuit breakers, which was open to the atmosphere. Each switchgear compartment was fitted with an arc flap on top, designed to release the pressure in case of an arc-flash. The bus bar, circuit-breaker and cable compartments were physically and electrically segregated in this design.

The enclosure for the harmonic filter was provided by Converteam and was constructed to provide an ingress protection (IP) of 44; this level of protection was selected by Converteam as an appropriate standard in order to prevent the cooling air inside the enclosure from escaping and meet the shipyard's specification.

1.12.3 Test of soot

In December 2010, a sample of the soot from the deckhead and a piece of insulating foam from a copper pipe passing under the deckhead of the aft harmonic filter room, were sent for analysis to a specialist laboratory. The purpose of the test was to investigate if substantial amounts of copper oxide were present in the soot, which would establish that an arc-flash had taken place. The report summarised that the soot comprised mostly of carbon, *presumably from burnt organic material which might include oil and polymeric material.* The analysis revealed iron; zinc or aluminium; and a few copper particles. No copper oxide was identified. A green deposit on the inside surface of the insulation was reported as *appeared to be copper chloride, possibly the result of a reaction of copper in a marine environment.*

1.12.4 Expert opinion

The Ministry of Defence (MOD) has procured a number of vessels with high voltage propulsion systems and has studied the potential risks from arc-flash incidents and how best to mitigate the hazards. Specialist MOD staff reviewed photographs of damage to the aft HF on *QM2,* and concluded that it was highly likely that an arc-flash occurred during the accident. Their observations are reproduced at **Annex G**.

1.13 *HI-FOG* FIRE SUPPRESSION SYSTEM

1.13.1 Manufacture and design

QM2 was fitted with a water-mist system, known by its trade name '*Hi-Fog',* that was designated as a water-mist system for local application fire-fighting in machinery spaces of category A[7]. It was manufactured by Marioff Oy, Finland and was installed when the vessel was built.

Parts of the system were fitted with different types of activation methods, intended to limit unwanted activation and consequent damage. The main machinery spaces were fitted with spray heads which required manual activation, achieved by operating a single button. The communication rooms, wheelhouse, safety centre, ECR, battery room, chart rooms, and pool rooms had a pre-action system. This required a flame or smoke sensor to trigger, activating a solenoid controlled valve which allowed water to enter the pipes and then flow through the spray heads. The accommodation spaces, including Deck B where the main switchboard rooms and harmonic filter rooms were located, all had spray heads with glass bulbs that were designed to break at an ambient temperature exceeding 57ºC.

The *Hi-Fog* piping system in the MSB and HF rooms was of the 'wet' type, filled with fresh water at 25 bars pressure. If a spray head was activated the system pressure would drop to 15 bars, activating the sprinkler pump accumulator unit. This delivered a pressure of 140 bars, which resulted in water being applied in the form of a fine mist. Water-mist was normally formed above 45 bars pressure. Depending on the number and location of the spray heads that had been activated, and whether there was trapped air in the line, design assumptions estimated that it could take up to 2 minutes for the high pressure water pump to cut in. It was possible to determine from machinery records on *QM2* that the high pressure water pumps started 6 minutes after the explosion occurred.

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[7] Machinery spaces of category A are those spaces and trunks to such spaces which contain either:

1. internal combustion machinery used for main propulsion;
2. internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power output of not less than 375kW; or
3. any oil-fired boiler or oil fuel unit, or any oil-fired equipment other than boilers, such as inert gas generators, incinerators, etc.

1.13.2 Design appraisal

The design appraisal was carried out by LR and was considered to comply with the following requirements:

- *SOLAS 1974, as amended, Chapter II-2/10;12.*

- *IMO Res. A800(19)*: IMO Resolution A.800(19) Revised Guidelines for approval of sprinkler systems equivalent to that referred to in SOLAS Regulation II-2/12.

- *MSC/Circ. 913*: Maritime Safety Committee circular MSC/Circ.913. Guidelines for the approval of fixed water-based local application fire-fighting systems for use in category A machinery spaces.

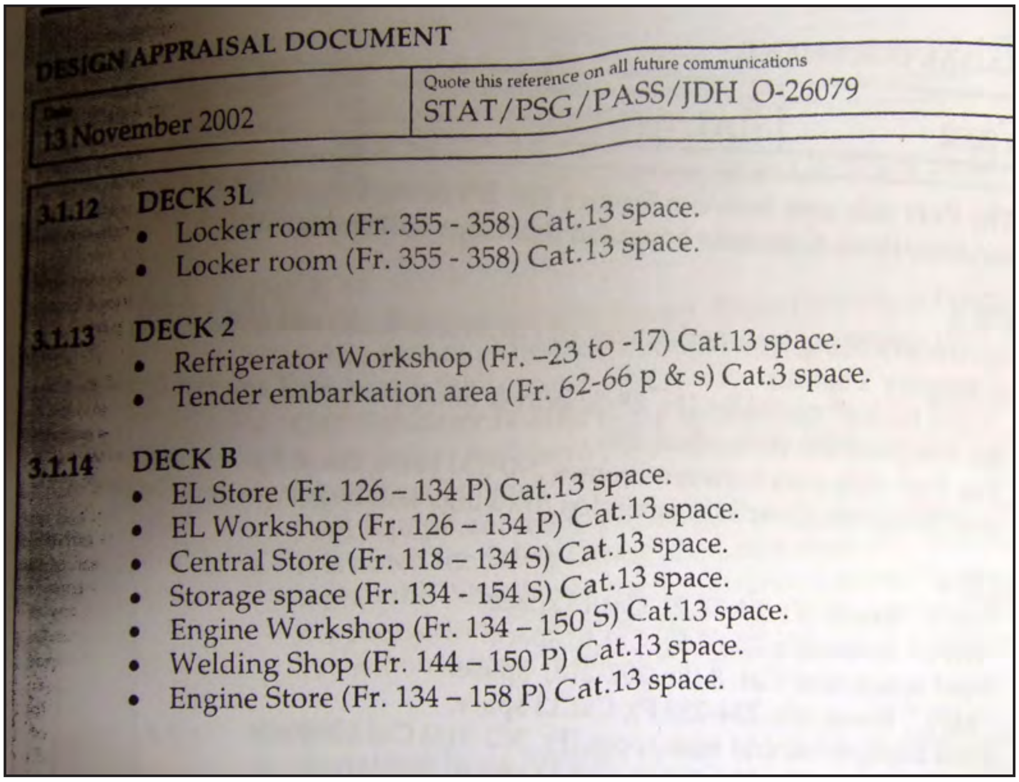
- *ISO 15371:2000*: Ships and marine technology - Fire-extinguishing systems for protection of galley cooking equipment.

- *IMO Res*. [sic] *668*: Maritime Safety Committee circular MSC/Circ.668. Alternative arrangements for Halon fire-extinguishing systems in machinery spaces and pump rooms Cargo pump Rooms.

- The Rules and Regulations for the Classification of Ships, Part 6, Chapters 1 and 2.

The design appraisal document listed all the locations where *Hi-Fog* spray heads were to be installed, beginning with decks 13 and 14 down to deck B under the section headed *'ACCOMMODATION SPACE Comments'*. The itemised list of compartments in deck B did not include the MSB or HF rooms **(Figure 24)** which were within this part of the ship. There was no record of these compartments being considered separately or in any other part of the design appraisal.

Figure 24



DESIGN APPRAISAL DOCUMENT

Date
13 November 2002

Quote this reference on all future communications
STAT/PSG/PASS/JDH O-26079

3.1.12 DECK 3L
- Locker room (Fr. 355 - 358) Cat.13 space.
- Locker room (Fr. 355 - 358) Cat.13 space.

3.1.13 DECK 2
- Refrigerator Workshop (Fr. –23 to -17) Cat.13 space.
- Tender embarkation area (Fr. 62-66 p & s) Cat.3 space.

3.1.14 DECK B
- EL Store (Fr. 126 – 134 P) Cat.13 space.
- EL Workshop (Fr. 126 – 134 P) Cat.13 space.
- Central Store (Fr. 118 – 134 S) Cat.13 space.
- Storage space (Fr. 134 - 154 S) Cat.13 space.
- Engine Workshop (Fr. 134 – 150 S) Cat.13 space.
- Welding Shop (Fr. 144 – 150 P) Cat.13 space.
- Engine Store (Fr. 134 – 158 P) Cat.13 space.

Itemised listing of areas fitted with *Hi-fog* outlets

In 2004, Marioff Oy conducted tests to demonstrate that it was safe to use the *Hi-Fog* system in high voltage compartments **(Annex H)**. At the time that *QM2* was built, none of the classification societies, including LR, had any explicit reference in their rules regarding the use of fixed water-based local application fire-fighting systems in compartments containing high voltage equipment.

1.13.3 Current regulations

The current LR Rules under Chapter 2 (Electrical Engineering), Section 16.3 Fixed water-based local application fire-fighting system (FWBLAFF) state:

> *High voltage equipment and their enclosures are not to be installed in protected areas or adjacent areas.*

Most classification societies require that electrical equipment in areas protected by FWBLAFF are to be contained in enclosures with ingress protection 44 (IP44). The FSS Code[8] refers to MSC Circular 1165, which in turn discusses the use of water-mist systems only in relation to category A machinery spaces. The only guidance available regarding the use of FWBLAFF in compartments with high voltage equipment is a footnote in IACS requirement E20. It states:

> *'Additional precautions may be required to be taken in respect of high voltage installations.'*

The IMO Maritime Safety Committee's sub-committee on fire protection agreed several revisions to MSC Circular 913 at its 54th session held in April 2010. However, the revisions did not include any reference to the use of FWBLAFF in high voltage compartments or enclosures.

1.14 POPULARITY OF ELECTRIC PROPULSION AND VARIABLE FREQUENCY DRIVES

A study carried out by the MAIB indicated that of all operational vessels over 100 gross tons, 1.85% have high voltage electric propulsion systems. Of the vessels which are being constructed, 4.10% are electrically propelled. Variable speed motors are becoming commonplace in new ships with electrically-driven propulsion, cargo pumps or other applications, benefiting from this technology. Modern liquefied natural gas ships predominantly use variable speed motors in their re-liquefaction plants. There are 545 vessels involved in offshore activities fitted with electric propulsion.

The major classification societies were asked to report how many vessels they had on their registers that used high voltage power systems. DNV reported that 319 vessels were registered which used HV electric propulsion, the majority using capacitor-based harmonic filters. Nippon Kiji Kyokai (Class NK) had 14 vessels registered as being in service and a further nine under construction. LR was unable to provide similar information regarding the number of vessels that were potentially at risk from similar problems.

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[8] The International Code for Fire Safety Systems (FSS Code)

At the time of publication, Converteam had supplied 65 vessels with synchro-converters and the majority of them were fitted with passive tuned filters using similar capacitors. Carnival UK and P&O Australia operate four vessels with HF systems identical to that of *QM2*.

1.15 SIMILAR ACCIDENTS

1.15.1 Capacitor failures

The circular on the hazards of polypropylene vapour which DNV distributed in 2007 to manufacturers of power converters was prompted by three accidents on board offshore support vessels. In the first case a smoothing capacitor, approximately 20 to 30kg in weight, fitted in the rectifier circuit of a 690V electric propulsion system exploded, blowing out the steel doors of its enclosures. In a second incident, a capacitor in a passive harmonic filter failed, resulting in the disruption of variable speed sea water cooling pumps for the low temperature cooling system. Detailed analysis by the manufacturers concluded that when the passive harmonic filter was lost due to capacitor failure, the harmonic distortion increased to approximately 20% which, in turn, affected the speed regulation system of the sea water pump motors, causing them to shut down. In a third incident, the harmonic filter enclosure panel was blown out when a capacitor exploded.

1.15.2 Arc-flash accidents

The IEEE Guide for Performing Arc-Flash Hazard Calculations, IEEE 1584-2002 (© 2002 IEEE[9]) contains a table of 49 arc-flash accidents in land-based installations. It contains details of voltage of equipment, activity undertaken at the time of the accident, and injuries sustained. This table is reproduced in **Annex I**.

In a study carried out by the MOD, 17 fatalities have been reported on non-UK submarines as a direct result of arc-flash incidents. The study also examined accidents on merchant ships that were likely to be attributable to an arc-flash fault. The following arc-flash accidents were identified:

- In 1990 *Regent Star*, a passenger vessel, suffered an MSB fire disabling the vessel mid-river.
- In 1993, the ro-ro vessel *Union Rotorua* experienced a fire in her 6.6kV MSB and had to be towed to port.
- In 1995 the passenger vessel *Celebration* had a major electrical fire in the ECR. *Sun Vista*, a passenger vessel, sank in Malacca Strait when her switchboard caught fire.
- In 2000, the passenger ferry *Columbia* was disabled following a fire in her MSB.
- In 2002, the passenger vessel *Statendam* had an arc-flash event in a main circuit breaker. This caused a fire which spread to other compartments, requiring the vessel to be towed to safety.

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[9] http://standards.ieee.org/

SECTION 2 - ANALYSIS

2.1 AIM

The purpose of the analysis is to determine the contributory causes and circumstances of the accident as a basis for making recommendations to prevent similar accidents occurring in the future.

2.2 THE ACCIDENT

2.2.1 Explosion

Although 'half drive alarm lamp' indications appeared on the P1200 alarm system, these were not readily apparent to *QM2* engine room watchkeepers. Even if they had been, their significance was not obvious, and it is considered unlikely that any of the watchkeepers would have interpreted them as early warning that a capacitor might fail catastrophically. They only became aware of the problem when they heard the explosion and saw the vessel black out. They established the location of the explosion by the thick black fumes emanating from the main switchboard room. The aft HF '*overload/unbalance*' alarm indication in the ECR; the alarm indicating the opening of the aft HF circuit breaker; the explosion; low voltage blackout followed by the stopping of main propulsion motors; and finally the shutdown of the generators, happened within a few seconds of each other. There was no opportunity for the crew to intervene, either to prevent the explosion or the subsequent loss of power.

<u>Ignition of dielectric vapour</u>

Evaluation of the failed capacitors established that considerable arcing had taken place between the foil layers. The presence of acetylene in the dielectric oil sample, even after the oil was exposed to atmosphere for several days, further corroborates this. Bulging of the capacitor cans could only have been as a result of internal pressurisation by vapour created by the breakdown of the dielectric insulation materials by internal arcing. The reduction in flash point caused by the mixing of this flammable vapour with explosive gases like hydrogen and acetylene would have increased the likelihood of the mixture being ignited by overheated or smouldering insulation material. Similarly, an arc between the opposing plates of the capacitor could also have caused ignition. The predominance of carbon found in the soot sample from the aft HF room confirms that burning of the vapour mixture had taken place.

<u>Electrical arc-flash</u>

The probable conditions that existed just before the accident: oil weeping or spraying out from the failing capacitor casing; 11kV voltage across the three phases; and the subsequent release of flammable gases from the capacitors, were ideal for an arc-flash event to take place. The melted corners of the copper bus bars indicate that arcing did take place between the phases, and it is therefore possible that the explosive noise heard by the crew members was due to the shock waves produced by the rapidly moving hot air emanating from the arc column. However, the majority of copper appeared to have melted and re-solidified instead of sublimating as in a classic arc-flash event, possibly explaining why copper oxide was not detected in the soot sample that was collected from the deckhead. It is also possible that much of the copper oxide was contained within the enclosure and was cleaned away before the sample was taken. One or more smaller arc-flash events could also have taken place in the past and been either undetected or unreported.

Cause

It is most likely that the explosion was due to a combination of both events: ignition of the volatile dielectric vapour released from the capacitor and an electrical arc-flash. While it is certain that these events were interdependent and occurred close together, it has not been possible to determine which was the trigger.

Irrespective of the cause of the explosion, the damage following it clearly demonstrated that the energy released was significant. It was extremely fortunate that there was no one in the vicinity when the explosion took place as the amount of energy released was easily capable of causing fatal injuries. This emphasises the potential danger to crew entering the harmonic filter room, especially to investigate an alarm. If the HF enclosure had been built to the same standard as high voltage switchgear, it would have had a built-in mechanism to release the explosive gases, the damage caused by the explosion could have been mitigated more effectively, and any crew nearby better protected. The case for uniform application of high voltage switchgear protection standards to all other high voltage equipment where crew intervention may be required during operation is therefore compelling.

2.2.2 Sequential blackout

Sequence

It was evident that the blackout was sequential rather than instantaneous. When the capacitor lifted up from the mounting it broke its connection to the 11kV line supply, thereby causing a loss of reactive power as indicated by the ‘IO-FAULT’ alarms at the 11kV bus bars and generators. The capacitor breaking its connections to the bus bars would have resulted in an open circuit in one of the three phases, and was most likely to have been the cause of the discrepancy alarms which indicated that the switchboard had detected a loss of one phase. The *single phasing* is likely to have triggered the negative sequence detection relay of the generators and would explain the subsequent tripping of the forward MSB bus tie breaker in accordance with the discrimination setting. This would also explain why the corresponding breaker on the aft MSB remained closed even after all the generators shut down. While this scenario is considered the most likely given the available evidence, it cannot be stated with certainty because the breakers had not been configured to record why each of them tripped.

It is also possible that during the accident, there was a short circuit or arc flash between two phases which could explain the voltage dip caused at the propulsion network bridge shown by the alarms on the P1200 system. However, it is not clear why the undervoltage alarm did not appear at the IAS. Although, the explosion and the failure of electric lights occurred almost simultaneously, the generators continued to maintain main voltage for approximately 16 seconds after the event, as seen in **Figures 11a** and **11b**.

These discrete events, occurring over several seconds, establish that the blackout was sequential, starting at the low voltage side of the network, subsequently affecting the high voltage side and finally resulting in all the DGs shutting down.

Cause of blackout

Without the information from each of the breakers, it was not possible to establish exactly why the generators shut down. The alarm sequence during the incident indicates that the HF circuit breaker opened first in response to the catastrophic event within rank 11.3, suggesting that its discrimination setting was correct. However, as they have yet to be verified, this cannot be confirmed.

A common cause for black out is a large variation of voltage within the network when a significant proportion of the electrical load is suddenly applied or abruptly disconnected. From the propulsion system alarm log, it is evident that all the propulsion motors' network bridges registered low voltage alarms, although each time they appear to have recovered to normal operating voltage. Surprisingly, there was no indication of low voltage on the IAS and it is therefore not clear why the generators shut down. It is likely that the high voltage network was unable to recover from the instability caused due to the disruptions within the aft HF.

It is highly likely that just before the accident, the two capacitors in the aft HF had degraded to such an extent that the ability of the 11.3 rank HF to absorb harmonics would have been severely compromised (see **Table 2** shown in section 2.3.3). It follows that the THDv just before the HF failed would have been significantly high **(Figures 12** and **13)**, perhaps causing the start of the electrical instability as indicated by the first alarm on one of the half drives of propulsion motor no. 3, around 36 minutes before the accident.

As the vessel was well away from traffic and not in congested or shallow waters, the loss of power for 30 minutes did not cause any navigational difficulties. However, losing control of a large cruise liner due to an electrical blackout, with 3823 people on board, is a serious concern. This accident demonstrates how electrical instability can cause unpredictable and potentially disastrous consequences in marine high voltage electrical networks. It is therefore necessary to consider how such transient events can be monitored and recorded to understand the exact nature and cause of electrical instabilities and the best way to mitigate them.

2.3 HARMONIC DISTORTION OF CURRENT AND VOLTAGE

2.3.1 Awareness

On conventional vessels with very few non-linear loads, harmonic distortion of current and voltage has not traditionally been an issue of concern. However, electric propulsion with variable speed AC motors is rapidly becoming the preferred method of propulsion on several types of marine vessels. Variable speed AC motors are also becoming more common as prime-movers in various auxiliary machines. The associated problems with harmonic distortion are therefore increasing. It is important that ships' crews gain a thorough understanding of the issue of harmonic distortion, so that they are better able to appreciate the importance of the harmonic mitigation equipment on board and take timely action if such equipment fails or deteriorates.

2.3.2 Simulations and trials

Although the likely THDv was calculated at *QM2*'s design stage in 2002 and measured during the vessel's sea trials in 2003, the effect of losing both harmonic filters was not considered. It may be argued that *QM2* was never intended to operate without an HF and could maintain her harmonic distortion levels within acceptable limits while maintaining service speed with one HF; therefore it was not necessary to model the case of the vessel operating without either HF. Nevertheless, due to the delay in the supply of spares, there were many occasions when the vessel had only one HF. As was demonstrated in December 2010, the one remaining HF could have failed at any time, leaving the vessel with no mitigation against harmonic distortion. Moreover, as there are no requirements from classification societies regarding redundancy in harmonic filters, many smaller vessels may only be fitted with one HF, and be operating in service with no guidance on the effect on ships' electrical systems should it fail.

The simulation study conducted by Converteam established that the THDv would have reached 22% had the propulsion plant continued to operate at 70% power output after the accident. It was fortunate that the undervoltage in the network bridge of the propulsion converters caused the power output to reduce to low levels; otherwise the consequences of operating at high levels of THDv could have been severe.

In December 2010, when *QM2* developed a defect on the forward filter, it was only the incorrect wiring in the protection system that prevented the circuit breaker from tripping, thus avoiding another potential blackout. The vessel was approaching port at the time and the potential consequences could have been very serious. However, the high imbalance current of 1250mA that was recorded at rank 4 of the forward HF was indicative of a capacitor in an advanced stage of degradation, and it was also very fortunate that the degraded capacitor did not fail catastrophically. As the crew had access to the recently completed theoretical modelling data, as well as an instrument with which to measure the harmonic distortion, they were able to manage the situation well and make the necessary repairs without compromising the safety of the vessel, the passengers or crew.

2.3.3 Monitoring and in-service verification

The measurements of THDv that were made during the sea trials in 2003 demonstrated that it was possible to maintain them within the 8% margins that were required by LR. However, no measurements were carried out with three DGs and one HF in use, the operating configuration just before the accident. While it would be impractical to expect the sea trials to cover all the possible combinations of generators, harmonic filters, power output, network configuration and measurement points, it would be sensible to verify the harmonic distortion levels in the highest risk and operating configurations used in service.

The comparison made in **Table 1** between the THDv measurements of 2003 and 2010 demonstrates an overall increase in THDv levels at all the measured points. As THDv in the network should not increase unless the network impedances have changed, the reason for this increase in harmonic distortion must be attributed to the difference in electrical loading conditions between the two measurements. This illustrates that THDv is not static and will change in operation, further reinforcing the benefit of continuous, or at least periodic checks.

Due to the internal circuitry of *QM2*'s HF capacitors, a short circuit in one element in a group of nine would result in the short circuit of the entire group, which would cause the capacitance of the remaining three groups to rise by 33%. If all four capacitor cans in one phase suffered the same degradation, the overall capacitance of that phase would have been 145µF, resulting in the de-tuning of the HF in one phase and resultant harmonic pollution **(Table 2)**. If the harmonic distortion had been continuously, or even only periodically monitored on board, the changes in THDv could have been easily detected and preventive actions taken before the capacitor failed catastrophically.

Capacitance(µF)	Harmonic order	Possible conditions
108.8	11.3	All elements in good condition
127.0	10.4	One element each shorted in two cans; two good cans.
136.0	10.1	One element each shorted in the three cans; one good can.
145.0	9.7	One element shorted in each of the four cans.
190.0	8.5	Three groups shorted in one can; three good cans.

Table 2: Illustration showing the variation of tuned harmonic order with internal degradation of capacitors in rank 11.3 of the harmonic filter. The values of harmonic order are calculated by MAIB using the relationship discussed in Section 1.8.1 assuming the capacitance changes in one phase only.

During the 3 days when MAIB evaluated the power quality on *QM2*, the aft HF was not available and only the forward HF was in use. It had a functional current imbalance detector and, as there were no alarms, it can be assumed that the capacitors in both ranks of the forward HF were in satisfactory condition, and the THDv levels would have been maintained within acceptable limits. However, the power quality of the vessel during the time prior to the accident when the aft harmonic filter was in use, would have been different. As the imbalance detector for rank 11.3 was defective, and the capacitors had degraded without being noticed, the unit would have become de-tuned and it is certain that the aft HF would not have been as effective as the forward one.

The overvoltage problems that were documented during the first year of the vessel's service, and again as recently as 2 weeks before the accident, were indicative that overvoltage conditions existed in the electrical network. The holes found on one of the capacitor elements were typical symptoms of overvoltage damage. This could have occurred during the accident, or even earlier in service; without continuous monitoring, transient overvoltage is hard to record, quantify or analyse.

The less frequent usage of the aft HF, reflected by its significantly lower running hours compared to the forward one, could perhaps be attributed to its unsatisfactory performance. It is common, when two machines are provided for the same purpose, that even though both work acceptably, one is more effective than the other and is preferred by the operators. It is quite possible that this occurred with the two HFs, and the aft unit was increasingly left as the stand-by, cutting in only to assist the forward HF and rarely used on its own. Had the harmonic distortion measurement equipment that was provided to the vessel been used, it would have given the crew some insight into the power quality and the comparative effectiveness of the two HFs on board.

Regular monitoring of power quality using a pre-determined pattern of propulsion motor loading with a complete record of operational parameters would help ensure that the harmonic distortion levels on board are closely monitored as the vessel and its equipment age and operating configurations change. An on-line monitoring system that records all the parameters and can be triggered to make specific recordings of transient voltage spikes or resonances, would be invaluable in assessing the ongoing quality of power. It would also be a very useful tool to investigate the root cause of accidents caused by anomalies in the electrical network and to identify incipient faults in these systems. Land-based utilities monitor their power quality as a matter of routine. In a marine vessel where harmonic distortion has the potential to disrupt its electrical network, the need for power quality surveillance is even more significant.

2.4 CAPACITOR FAILURES

2.4.1 Initiation of failure

Construction, design and rating

QM2's HF capacitors were manufactured by Vishay, one of the leading suppliers of this product with an established global supply chain. Converteam's audits of Vishay's processes had not revealed any deficiencies, and established that the manufacturing and testing process adhered closely to IEC 60871 parts 1 and 2. The independent tests carried out on behalf of MAIB did not reveal any major flaws in construction, except the creasing on the capacitor element foil in one capacitor element. Nevertheless, the overall design and construction of the capacitor was acceptable and met Converteam's specification.

The capacitors' voltage rating of 8242V was 30% in excess of the expected voltage across the capacitors connected in their star configuration. From examination of the specification it is considered that Vishay had exceeded the requirement from Converteam to consider the harmonic voltages up to the thirtieth harmonic in addition to the fundamental frequency. Therefore, it is highly unlikely that the capacitor was under-rated by design, even when considering the increased voltages due to inductive effects. Where switching transient overvoltage is concerned, LR rules, which allow a 20% increase for a period of 6 to 7 seconds do not match the equivalent IEC requirement which allows for a much larger transient voltage lasting half a cycle or 1/120 of a second (considering 60Hz fundamental frequency). As the requirements of IEC 6087 pertain specifically to high voltage capacitors and the LR rules are more general, it would be logical in the longer term for LR to reconsider their rules on transient overvoltages when they specifically apply to capacitors.

The maximum temperature recorded on the surface of one of the forward HF capacitor cans was 49ºC, during winter conditions; therefore, higher temperatures were likely to occur during tropical weather. However, the circulating air temperature in the forward filter as indicated in **Figure 23** was well within the permitted value. Assuming that the cooling system had sufficient capacity to maintain the ambient temperature below 45ºC even under tropical conditions, it is unlikely that the degradation was caused by high ambient temperatures. The effect of the alarm thresholds being set too high at 47°C was not thought to add significantly to the risk of a high ambient temperature. The long-term effects of the higher surface temperatures on the capacitor cans was less clear and would merit further monitoring and consideration.

Switching frequency

The IEC standard's requirement for capacitors to withstand 1000 switching cycles in a year (an average of 2.7 a day), is based on an example of a land-based installation where the operation pattern exhibits minimal variation on a daily basis. On a vessel like *QM2*, that has a widely varying operating pattern, it could be necessary to vary propulsion speed quite frequently, requiring the standby harmonic filter to be switched in and out several times during the day. Even though it was out of service for some time, the 10,000 hours difference in running hours between the filters indicates that the aft HF was predominantly used as the second filter and therefore subject to more switching operations than the forward one. It is therefore considered that both HFs could have experienced more switching cycles than expected in a land-based installation, with the aft HF being more at risk.

While the standards and specifications for land-based HV equipment and installations provide valuable guidance, it must be accepted that the conditions and operating patterns in marine installations can differ substantially. It is therefore essential that the effects of these differences are understood and that design margins are increased accordingly.

Summary

The capacitor manufacturing process satisfied the criteria of the IEC standard and met Converteam's specification. However it is likely that the capacitors started to deteriorate far sooner than their expected lifetime of 20 years due to the operating conditions being harsher than expected. The initial degradation of the capacitor was likely to have been caused by one or both of the following:

- being subjected to voltages in excess of their design rating
- being exposed to frequent voltage transients due to increased number of switching cycles

Failure initiation due to minor manufacturing anomalies such as the existence of stress raisers on the capacitor elements, though less likely, cannot be completely ruled out.

2.4.2 Progression to catastrophic failure

Once initiated, the damage on the solid components in the dielectric medium would have become a weak spot and the most likely location to suffer further arcing. Although the dielectric oil had self-healing properties and could absorb some of the damage done by partial discharge or arcing, the deterioration of the solid insulation would have been permanent. The process would have continued until one of the elements in a group of eight suffered a short circuit, thereby shorting the group and increasing the voltage across the remaining groups by 33%. A complete short circuit of one group would have developed an imbalance current of 1300mA, far in excess of the trip current of the current imbalance detector. If the imbalance detector had been functional, the aft HF breaker should have tripped and taken the HF off-line; the capacitor damage would have been detected long before it reached the critical point where an explosion would occur.

As the deterioration progressed, the voltage across the last group of remaining capacitor elements would have increased to a maximum of 400% of the rated voltage leading to heavy arcing and rapid vaporisation of the dielectric oil and the polypropylene film. There was no way to release the vapour, and the internal pressure would have increased until the capacitor casing ruptured at the welded joint at the base. The pressurised oil and vapour would have escaped downwards with substantial velocity, resulting in the entire can lifting up, breaking free from its foundation, disconnecting itself from its bus bar and damaging neighbouring capacitors in the phase group.

The SOLAS requirement for machinery systems that are normally under pressure to have pressure relieving arrangements could be interpreted to include only those systems which contain a fluid under pressure. However, some systems could be pressurised under abnormal operating conditions, as illustrated by this accident. An analogy is the water jacket of a high pressure air cooler in an air compressor, which is required to be provided with a bursting disk, in case pressurised air leaks into the water side. It is imperative that equivalent means are provided in HV components, either to relieve the excess pressure; warn the operator with alarms; or shut down the system to prevent further pressurisation. The inherent hazard of sudden and uncontrolled release of pressure energy from electrical devices such as capacitors needs to be recognised and addressed as a matter of priority.

2.4.3 Design changes in new capacitors

Some of the changes made to the design of the capacitors that were fitted after the accident - especially the change in the configuration of element groupings resulting in the decrease of voltage across individual elements by 20%, and the thicker polypropylene film with a better gradient of electrical strength - appear to be a natural reaction of any manufacturer to make their product more robust while the root cause of failure remained uncertain. The fitting of internal fuses and pressure sensors recognises the non fail safe nature of the current imbalance transformer and augments the protection provided by the imbalance detection system.

If the capacitor elements were individually fused, the degraded elements would have been isolated and the whole unit would have continued to function for a longer period. Nevertheless, similar failures on other units could eventually lead to progressively increasing voltages across the healthy units, eventually leading to a catastrophic failure with similar consequences. The decision to fit pressure sensors on the transformer oil tank recognised the risk of arcing and internal over-pressurisation by the oil vapour. It was unfortunate that the same reasoning did not extend to the protection of capacitors, even though the capacitor information brochure by Vishay, as well as academic papers on the subject, clearly identified these risks. This accident demonstrates the importance of designing in safety features in HV electrical devices.

2.4.4 Maintenance and replacement history

The maintenance history for the HFs was sparse and contained insufficient details of the failure mode, serial numbers of failed units, or the ranks they were fitted in. However, it was possible to determine that at least six capacitors had been replaced due to internal failure of capacitor elements. Despite such a relatively large number of failures, there were no attempts to analyse the cause. The crew accepted the rate of failure as one of the unavoidable features of the new technology, and did not question it further. The frequent mechanical damage suffered by the capacitors during transit possibly masked the fact that, on average, one capacitor was being replaced each year due to internal degradation.

Technical managers did not recognise this trend as the capacitors were just a few components among many thousands, and so were unable to take any preventative action. They were not aided by their maintenance system, which did not analyse the rate of failure or alert them to the unusually high consumption of replacement parts. In contrast to the transformers, there was no facility to test the condition of the capacitor's dielectric fluid and, despite this being a condition of the CSM survey, the impossibility of this task was not recognised by either the crew or LR. As HFs had not been included in the list of critical equipment on *QM2*, another opportunity to recognise and act upon the frequent failures was lost. Neither Converteam, the original equipment supplier, nor Vishay, the capacitor manufacturer, identified the high consumption of capacitors on board *QM2*.

Component failure can often be a symptom of an underlying problem with the equipment or system. Ship managers and crew should be more alert to this, particularly with new technology. Maintenance management and associated parts' requisition systems should be used to record component failures in sufficient detail to allow more meaningful analysis and give an early warning to prevent more serious problems.

2.4.5 Current imbalance detection system

The capacitor exploded because the inoperative imbalance detection system could not identify the deterioration of the capacitors. The failure of the imbalance system's current transformer remained undetected for what could have been several years. It is certain that this system was not working in 2008 when Converteam detected two defective capacitors during a routine check in dry dock because no imbalance alarms were recorded by the IAS system at the corresponding time. Further examination of the maintenance history established that, of the five capacitors replaced in rank 11.3, four took place in dry dock as a result of routine checks, rather than because of an imbalance current alarm. Although the windings of the current imbalance transformer were tested during manufacture, subsequent tests of the system were by secondary current injection, bypassing the windings. As the IAS did not specifically register which rank of the HF had developed an imbalance current, it was not possible to confirm if the current imbalance transformers on rank 11.3 had ever worked in service.

It is concerning that none of Converteam, the ship's engineers and Carnival's technical management team questioned why the current imbalance detection system had not registered an alarm when two capacitors were found degraded during routine checks in October 2008. Although Converteam's inspection report indicated that the protection systems had not been tested, no questions were raised.

Even if the protection systems had been tested, this would probably have been by secondary current injection, as done during the factory acceptance test. This method would have bypassed the current transformer and an open circuit fault in a transformer winding would have gone unnoticed. Even though an annual test of the protection system was required by Converteam, it is disconcerting that there was no record of this having been done.

Although there was no requirement on Vishay for the current imbalance transformer to conform to IEC 60044-1 as it had not been specifically requested by Converteam, it is nevertheless considered the appropriate recognised standard for measurement and protection transformers. It is unfortunate that, when audited against IEC 60044-1 after the accident, 15 of 23 requirements were not met. These shortcomings were likely to have contributed to the premature failure of the transformer. In addition, there was no verification of the HF protection system during the factory acceptance tests. While the production of capacitors was strictly controlled and carried out in accordance with the applicable standards, the transformer, at the heart of the monitoring and protection system, was constructed and put into service without the same diligence. LR, whose representatives were present at the factory acceptance test, accepted a superficial test of the protection system, which did not include a check of the transformer.

Although the current imbalance detection was the only protection system for the HFs, it had no back-up and did not fail safe. The only possible indication of a failed protection system would have been a 000mA reading on the imbalance current display. However, since neither the instruction manual nor maintenance system mentioned this, and that a ‘good’ reading would have been a few 10s of mA, it was highly improbable that the crew would have appreciated the significance of this subtle distinction. Protection systems for critical equipment, especially when there are no alternative or back-up systems, must be fail safe. They should also be tested at regular intervals to verify that all the sub-components in the system are functional. Greater, and more careful, consideration of the protection systems provided for mitigating the failure of HV equipment, is required.

2.5 HIGH VOLTAGE ENCLOSURES

2.5.1 Protection

There was evidence to support that an arc-flash had taken place during this accident on board *QM2*. Considering the recurrent problems with the vessel’s damaged and leaking capacitors, it is also possible that one or more such events might also have taken place in the past.

In the design of electrical equipment for the marine industry, insufficient consideration is given to its ability to withstand an arc-flash event. The requirement of classification societies for protection against arc-flash is limited to high voltage main switchboards on the premise that the risk of an arc-flash event injuring a crew member is more prevalent in a switchboard, where manual operation of circuit breakers may sometimes be necessary. However, as was the practice on *QM2*, the HF room was entered routinely by the crew to inspect the HF components. They also tended to enter the room when the HF alarm had activated, and the HF equipment was therefore in its most dangerous condition. The vessel operated with a defective protection system and incorrectly wired trip circuits; it is therefore very fortunate that an explosion did not take place while someone was inside the HF room. This accident demonstrates that it is no longer tenable to restrict arc resistant measures to main switchboards alone.

2.5.2 Awareness of arc-flash

Although the COSWP covers high voltage work permit and sanction-to-test procedures, there is no mention of the hazards of arc-flash. Awareness of arc-flash hazards needs to improve throughout the marine industry so that designers, builders, owners, operators and engineers understand the problems and the potential risk reduction measures available to reduce the hazard to as low as is reasonably practicable. It is important that the hazards of arc-flash and the personal protective equipment which could help prevent injury when working near live electrical equipment be incorporated into the COSWP at the earliest opportunity.

2.6 ALARM MANAGEMENT

During the watch before the accident, the duty engineer accepted approximately one alarm every minute. It is highly likely that the number of alarms during the busy hours of the day would have been even higher. The purpose of an alarm is to alert the watchkeeper to an anomaly so that appropriate corrective actions may be taken. However, if the alarms appear as frequently as one every minute, it would be almost impossible for the watchkeeper to deal with them effectively. Half an hour before the accident, the duty engineer had accepted two fire alarms without taking any further action and without actually knowing at the time that these were false alarms.

Although during this accident there were no alarms on the IAS to warn the watchkeeper of the impending explosion and blackout, a series of ‘half drive lamp alarms’ began to appear on the P1200 system starting 36 minutes before the accident. The frequency of alarms on the IAS at around one every minute, in addition to alarms from the P1200 system is most likely to have overwhelmed the watchkeeper, and it is not surprising that the propulsion motor alarms were not acted upon. Therefore, it is imperative that ship managers, in consultation with the class society concerned, carefully review machinery alarms to make sure that crew are warned about major equipment failures and that alarms are prioritised to focus on the areas most critical to maintaining the safety of the ship.

2.7 WATER-MIST IN HIGH VOLTAGE COMPARTMENTS

It was apparent that the design appraisal process for the *Hi-Fog* system did not include the MSB and HF rooms; these compartments were not included in the appraisal document. Whereas several critical locations such as wheelhouse, communication room and ECR were fitted with a pre-activation system, and the machinery space required manual intervention to release water, the MSB and HF enclosures were fitted with the most basic ‘wet’ pipe system as used in the accommodation, which released water as soon as the sprinkler bulb ruptured. It is unlikely that this type of system, with the risk of a pressurised pipe leaking in service and spraying water on to the high voltage enclosures and equipment, would have been selected if these compartments had been included in the appraisal process.

Although the HF enclosures satisfied LR’s requirement to meet IP44 standards, this had been done in order to provide an effective means of containing the cooling air and meet the shipyard’s specification rather than as an overt means of protection against water mist. The HF enclosure was severely disrupted as soon as the explosion occurred and was unable to maintain protection to IP44 standard thereafter.

All the IMO reference documents against which the appraisal was carried out, pertained to machinery spaces of category A; it is unlikely that the suitability of using FWBLAFF systems in high voltage areas was thoroughly considered or discussed.

There was no evidence to suggest that the water spray, which was sustained for 6 minutes, or the subsequent water-mist, interfered with the high voltage equipment. The ship had suffered a complete blackout of all systems within less than 20 seconds of the explosion, and the electrical network was dead with the possible exception of stored energy in components due to capacitive effect. It was fortunate that the two engineers who entered the compartment immediately after the blackout, while considerable water was sloshing about on the deck, did not come into contact with any charged components. The consequences would almost certainly have been fatal.

Although tests conducted by Marioff after *QM2* was delivered, demonstrated that the *Hi-Fog* system was safe for use in a high voltage environment, there is no record that these test results have been endorsed by the IMO or IACS. There is little or no guidance on this subject in the FSS Code or class rules. LR's current rules are confusing, explicitly prohibiting the installation of high voltage equipment or enclosures in areas protected by FWBLAFF systems in one part yet allowing FWBLAFF systems in areas containing electrical equipment with IP44 rated enclosures. It is therefore necessary for the class rules to be reviewed, with the aim of removing such inconsistencies and ensuring that installations are properly considered. The FSS Code may also need to be amended in due course to include appropriate guidelines for the use of FWBLAFF systems on high voltage equipment and enclosures.

SECTION 3 - CONCLUSIONS

3.1 SAFETY ISSUES DIRECTLY CONTRIBUTING TO THE ACCIDENT WHICH HAVE RESULTED IN RECOMMENDATIONS

1. It is likely that the initial degradation of the capacitor was due to one or both of two anomalies: being subjected to voltages in excess of their design rating, or being exposed to frequent voltage transients due to increased number of switching cycles. Instances of failure initiation due to minor manufacturing anomalies, though less likely, cannot be completely ruled out. [2.4.1]

2. Certain engineering systems could be pressurised under abnormal operating conditions. The inherent hazard of internal pressurisation of harmonic filter capacitors, and the sudden and uncontrolled release of pressure energy from them was not considered. [2.4.2]

3. The capacitor explosion could have been prevented if the current imbalance-based protection system was functional. The protection system was not designed to fail safely; it is possible that the failure of its transformer remained undetected for several years. There is no evidence of the protection system being tested during the service life of the vessel. [2.4.5]

4. The first possible indication of the developing accident was available at the P1200 propulsion monitoring system around 36 minutes before the accident. The sheer volume of alarms from the IAS at around one every minute, in addition to alarms from the P1200 system, is most likely to have overwhelmed the watchkeeper and it is not surprising that the propulsion motor alarms were not acted upon. [2.6]

3.2 OTHER SAFETY ISSUES IDENTIFIED DURING THE INVESTIGATION ALSO LEADING TO RECOMMENDATIONS

1. This accident highlights the dangers to the crew when entering the harmonic filter room, especially to investigate an alarm. If the harmonic filter enclosure was built to the same standards as high voltage switchgear, the damage caused by the explosion could have been mitigated more effectively. The case for uniform application of high voltage switchgear protection standards to all other high voltage equipment, where crew intervention may be required during operation, is therefore compelling. [2.2.1]

2. Losing control of a large cruise liner due to an electrical blackout, with 3823 people on board, is a serious concern. This accident demonstrates how harmonic distortion can lead to electrical instability and cause unpredictable and potentially disastrous consequences in marine high voltage electrical networks [2.2.2]

3. As variable speed AC motors are becoming more common for propulsion as well as for auxiliary machinery prime movers, ships' crew will be exposed to various types of harmonic mitigation equipment. It is important that ships' crews gain a thorough understanding of the issue of harmonic distortion and harmonic mitigation equipment, so that they are better able to appreciate the importance of the equipment on board and take timely action if such equipment fails or deteriorates. [2.3.1]

4. In December 2010, when QM2's forward HF also failed, the crew had access to modelling data on the expected level of total harmonic distortion of voltage when all harmonic filters fail, and an instrument with which to measure the harmonic distortion under these circumstances. They were therefore able to manage the situation well without compromising the safety of the vessel or her passengers and crew. [2.3.2]

5. In a vessel where electrical instability has the potential to disrupt its electrical network, possibly leading to a blackout and loss of control in restricted waters, the need for power quality surveillance is significant. Regular monitoring of power quality, using a pre-determined pattern of propulsion motor loading with associated motor operating parameters, would help ensure that the health of electrical equipment on board is closely monitored as the vessel and its equipment ages and usage patterns change. [2.3.3]

6. Although QM2's current imbalance detection was the only protection system for the harmonic filters, it had no back-up and was not fail safe. Protection systems of critical equipment, especially when there are no alternative or back-up systems, must fail safe. They should also be tested at regular intervals to verify that all the sub-components in the system are functional. [2.4.5]

7. Awareness of arc-flash hazards needs to be significantly increased throughout the marine industry, so that designers, builders, owners, operators and engineers understand the hazard, risks and the potential risk reduction measures available to reduce the hazard to as low as is reasonably practicable. Although the COSWP covers high voltage work permit and sanction-to-test procedures, it does not mention the hazards of arc-flash. [2.5.2]

8. There is little or no guidance regarding the use of fixed water-based local application fire-fighting systems in compartments with high voltage equipment. LR's rules on the subject provide conflicting guidance. [2.7]

9. The failure to identify the trend of high consumption of capacitors on board QM2 was a major contributory factor in this accident. Component failure can often be a symptom of an underlying problem with an equipment or system. Ship managers and crew should be more alert to this, particularly with new technology. [2.4.4]

SECTION 4 - ACTION TAKEN

The **Marine Accident Investigation Branch** has:

- In December 2010 published a safety bulletin, informing the industry of the accident and providing guidance on checks to detect impending capacitor failures **(Annex J)**.
- Issued a flyer to the shipping industry with this report, which details the lessons learnt from the accident **(Annex K)**.

Carnival PLC has:

- Included harmonic filters in its list of critical equipment for *QM2*, and has ensured that procedures exist for regular testing of their protection systems.
- Developed and implemented procedures for dealing with harmonic filter imbalance alarms and entering harmonic filter rooms after an alarm has activated.
- Replaced all the capacitors in *QM2*'s aft harmonic filter.

Converteam has:

- Issued a service bulletin alerting its customers to the potential for catastrophic failure of its capacitors and the circumstances that could lead to this.
- Replaced the capacitors in *QM2*'s aft harmonic filter with an improved and safer design.
- Carried out a quality audit of the capacitor manufacturer.

Lloyd's Register (Europe, Middle East and Asia) has:

- Progressed with existing work to review its rules to recognise and mitigate the hazard of arc-flash associated with harmonic filters fitted in high voltage electric networks.
- Changed the Continuous Survey of Machinery requirements to remove the need to test samples of dielectric fluid from capacitor cans.

SECTION 5 - RECOMMENDATIONS

Lloyd's Register (Europe, Middle East and Asia) is recommended to make a submission to IACS to develop a unified requirement to:

2011/149 Improve the standards of protection that are required against harmonic distortion and component failure in vessels operating high voltage networks, to ensure:

- there is a requirement in all new-build vessels that may be affected by harmonic distortion of current and voltage that:

  In the event that all harmonic mitigation systems fail, information is provided on board to describe the maximum extent of harmonic distortion that can be expected.

  Guidance is provided so that crew can take effective action to keep power and propulsion equipment operating (at an appropriate power output) if harmonic mitigation equipment degrades or fails.

- On-line monitoring of harmonic distortion of voltage is required for new build vessels and, for existing vessels, there is periodic monitoring to detect change or degradation of harmonic distortion levels.

- Specific requirements are developed to detect and mitigate against the failure of high-energy storage devices such as capacitors.

2011/150 Review the requirements for the enclosure of high voltage systems to ensure that the degree of protection is consistent for all equipment where crew intervention could be required and the hazard from arc-flash exists.

2011/151 Introduce a specific requirement ensuring that where the failure of an equipment or machinery may lead to serious damage to the vessel, or injury to personnel, its protection system must be of a 'fail safe' type.

Lloyd's Register (Europe, Middle East and Asia) is also recommended to:

2011/152 Review and clarify its rules on the installation of fixed water-based local application fire-fighting systems in compartments containing high voltage systems and, through IACS, propose the appropriate amendments to incorporate this guidance in the FSS Code.

The **Maritime and Coastguard Agency** is recommended to:

2011/153 Using this report and the accompanying safety flyer as a basis, publish a marine guidance notice to raise awareness of the potential hazards of excessive harmonic distortion of current and voltage.

2011/154 Review and update the Code of Safe Working Practices for Merchant Seamen (COSWP) to provide more detailed information on the hazards associated with high voltage equipment, including arc-flash.

Carnival UK is recommended to:

2011/155 Improve the standards of protection against the effects of harmonic distortion and component failure by:

- Instigating a programme of modelling or other appropriate means to develop safe vessel operating parameters and procedures to be used in the event of harmonic filter failure.
- Ensuring that *RMS Queen Mary 2*'s maintenance system identifies all critical high voltage system protection devices, and contains procedures for periodic checks to confirm that they function correctly.
- Implementing a method of identifying and analysing unexpectedly high rates of component failures in harmonic filter equipment and other high voltage systems.

2011/156 Review the machinery alarm systems fitted to *RMS Queen Mary 2* in order to identify those alarms which indicate failure conditions that could significantly affect the safety of the vessel. In doing so, action should be taken to prioritise such alarms above others that relate to the more general operation of the ship, so that operators can more readily recognise complex system failures and respond appropriately.

Marine Accident Investigation Branch
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Marine Accident Report