Wave Energy Converter System Safety Analysis

U. Okoro#1, A. Kolios#2, P. Lopez#3, L. Cui*4, Q. Sheng+5

#School of Energy, Environment and Agri-Food, Cranfield University
Bedfordshire MK43 0AL, United Kingdom

1u.g.okoro@ cranfield.ac.uk
2a.kolios@cranfield.ac.uk
3epl@cranfield.ac.uk

*National Ocean Technology Center
219,West Jieyuan Road,Nankai District, Tianjin, China
4cuilin_oceanenergy@126.com

+ Institute of Ocean Renewable Energy System, Harbin Engineering University
Harbin, China

5shengqihu@hrbeu.edu.cn

***Abstract*—Safety Intervention Decisions made at early design stages of a system have more significant impact on operational performance than at any other stage in its lifecycle. But, early risk-based decisions for novel offshore installations such as Wave Energy Converters (WEC) are hampered by dearth of much needed failure information. To support such decisions on development of a Point-absorber type WEC with a hydraulic Power Take Off (PTO), Functional Failure Mode and Effect Analysis (FFMEA) and Hazard and Operability Study (HAZOP) were used independently to study the potential functional failures of the system at different stages of the development. FMEA is employed to perform assessment of the potential risk in the early stage of the design while HAZOP to reveal risk consequences of functional failures of subsystems and component at the operations and maintenance stage of the lifecycle. The system was decomposed into 21 elements; a level considered appropriate to expose all potential functional failures. The highlight of the work is presentation of exhaustive FMEA and HAZOP sheets meant to feedback failure mode and reliability information into design of Wave Energy Converter System with a hydraulic PTO**.

***Keywords*—Wave Energy, Point absorber, Hydraulic Power Take-Off, System Safety, FFMEA, HAZOP**

I. INTRODUCTION

Cutting down on OPEX has been the driver behind numerous designs of WEC. However, this must be sought with system safety in mind. A Through-life safety approach [1] systematically identifies system hazards, assesses and evaluates risks at each stage of a facility's life and the level accepted or rejected by appropriate decision authority. However of most concern is operation and maintenance phase given that risk due to functional failures of components, equipment or systems constitute a greater proportion of the Major Accident Hazards in most industries [2]. An early design stage safety intervention decision reduces cost of implementation and improves operational performance than at any other stage in its lifecycle. However, for novel offshore installations such as WEC making such risk-based decisions are challenged by lack of much needed failure information.

Currently, knowledge of significant failures are been gained through deployment and testing of large scale prototypes WECs [3] such as the CORES project, Oyster project from Aquamarine Power, Archimedes Wave Swing from AWS Ocean Energy etc.[4]. Such information compliments safety studies [5] needed before final design and production. The focus of this paper is to augment current efforts in WEC design decision making using safety studies FFMEA identify failure modes not foreseeable to be designed out in the early stage of design and development while possible deviations from the design intent during Operational and Maintenance phase was analysed using HAZard and OPerability studies (HAZOP). Both methods are implemented strategically in design for safety of Wave Energy Converter (WEC) as presented in this paper.

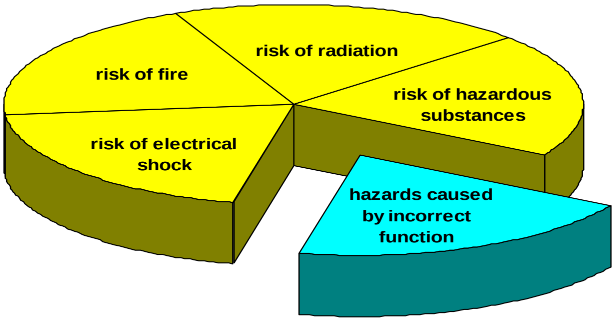

Fig 1 Proportion of total operational risks [6]

TABLE I
CAUSE OF MAJOR ACCIDENTS IN PERIOD BETWEEN 1985—2001 [2]

Cause of accident	Contribution (%)
Equipment failure	44
Equipment failure and Human	21
Human	19
To be defined	9
Equipment failure and Environment	4
Environment	3

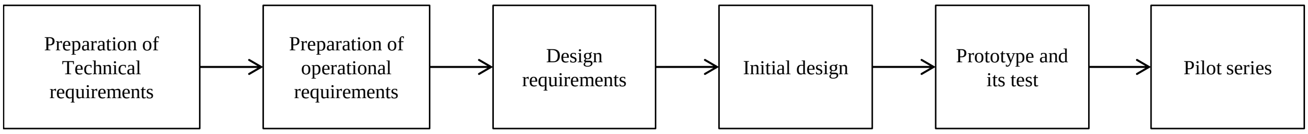

Fig 2 Design and Development stages of WEC

II. FFMEA and HAZOP ANALYSES

FFMEA also referred to as system FMEA is a proactive tool that identifies functionality and features that will make the system more robust and failure resistant during operation. It systematically identifies, documents, and prioritises potential functional failures modes of a system during operation, their effects and causes using engineering knowledge, reliability, and organisational development techniques. A well performed FFMEA answers the following questions; what might go wrong with the system? –What effect would this failure have? –How significant is it if it occurs? –What might cause the failure? –How often will it occur? –How likely is it that we can find it? [7].

Components of subsystems are designed to interrelate in a predetermined way to achieve the aim(s) of the system. Therefore potential deviation may lead to systems hazards. Fed by experience from the original intent of process design and operations, HAZOP technique identifies and analyse hazards and operational concerns of a system due to potential functional deviations from original intent of process design through the unique use of key guide words. The deviations from the intended design are generated by coupling selected guide words with a variable parameter or characteristic of the plant, process, or system. HAZOPS methodology [8] involves taking a full description of a system and systematically questioning every part of it to establish how deviations from the design intent can arise. Once identified, an assessment is made as to whether such deviations and their consequences can have a negative effect upon the safe and efficient operation of the system. Data required for HAZOP analysis consist of various drawings in the form of line diagrams, flow sheets, facility layout, isometrics and fabrication drawings, operating instructions; instrument sequence control charts logic diagrams, and computer codes, facility and equipment manufacturer's manuals.

III. MODELLING OF GENERIC WEC WITH A HYDRAULIC PTO SYSTEM

The system consists of sea-wave, a system of Floater and Arm, Kinematic link Mechanism, Hydraulic cylinder, a system of High pressure pipes, a Directional Control valve, Accumulators, Hydraulic motor, Oil reservoir, Low Pressure Line, Generator, inverter, and Power grid as shown in Fig 3.

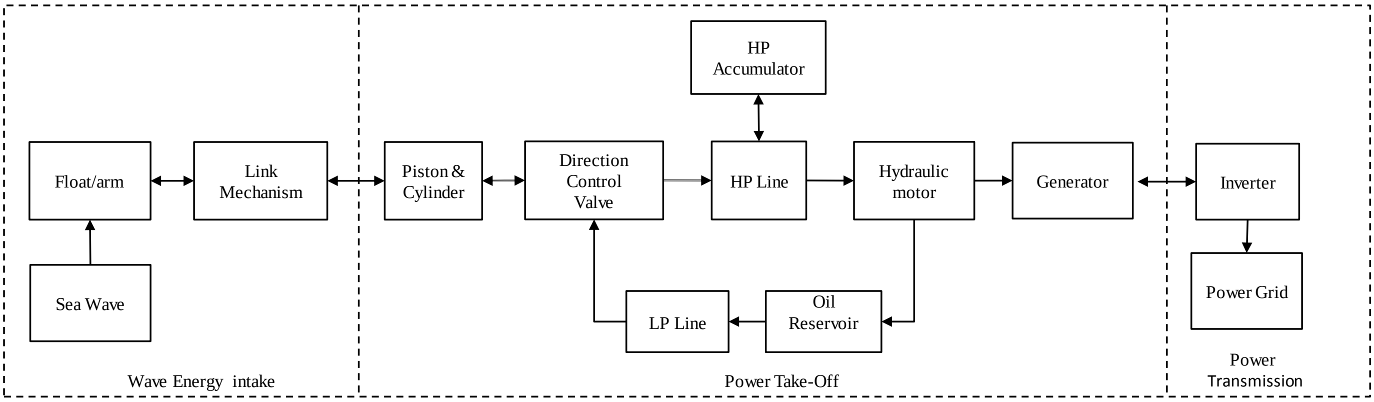

Fig 3 Description of WEC System

A. Detailed working principle of Hydraulic PTO

The working principle of Wave Energy Converter based on Hydraulic Power Take-Off follows physical law of conservation of energy; floaters interact with the sea-waves in such a manner to reduce the amount of wave energy that is otherwise present in the sea. Thus the device must generate waves which interfere destructively with the waves of the sea [6]. The waves apply excitation force to floater-arm mechanism which in turn responds by resisting the work done on it by the force. The resulting equal and opposite reaction (by Newton's third law), is transmitted through a link to acts on a rod of a double acting cylinder and does work on fluid in the different chambers of the cylinder. Inside the cylinder chambers, two cycles are in force. In the forward stroke, the fluid's energy is raised and the fluid is forced out through port A to the High Pressure (HP) Line. In turn, differential pressure thus created sucks fluid in from the Low Pressure (LP) Line through port B. During downward stroke, the reverse happens; high energy fluid is forced out through port B to the HP line while intake from the LP line happens through port A. The switch over of port A to HP line and port B to LP line and vice versa as the case may be is controlled by the Directional control valve (DVC). Once out of the port, the HP fluid flows through HP lines to a Hydraulic motor where it drives a turbine to cause a rotary motion of a shaft linked to a generator. The generator drives an electrical machine which generates electricity. Often, a HP accumulator is used to create and maintain a fluid flow gradient. This mechanism is Power Take-Off [9].

B. *WEC components design intent.*

In order to achieve its goal, each components of the WEC system must consistently function in a particular manner as defined by the design intent. Table II shows the design intent of the main components of the WEC system.

Table II DESIGN FUNCTION OF COMPONENTS of WEC

Components	Parameter
Wave	Excitation torque τ_{ext} due to an incoming irregular wave
Float /arm	Angular position θ_{arm} and Velocity ω_{arm} of the arm
Kinematics	Torque applied by PTO to the float/arm τ_{PTO}
	Stroke of the cylinder X_c, Velocity of stroke V_c
Cylinder	Force of cylinder, F_c
	Pressure of fluid, $P_{A,}$, P_B through chamber A and B respectively of the cylinder.
Hydraulic Motor	Fluid flow rates, $Q_{A,}$ $Q_{B,}$ into cylinder chambers A and B respectively.
	Motor Torque, $\tau_{M,}$
Generator	Angular velocity, $\omega_{G,}$ and Output power $P_{out,}$

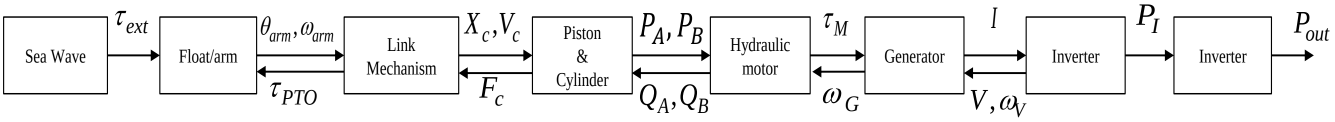

Fig 4. Functional diagram of WEC system showing components interactions [10]

C. *Analyses and Result*

Analysis starts with decomposition of the WEC system into 22 components. For each component, functions performed in the system were defined (a total of six functions), as well as possible ways failure could occur (total of 10 failures). Then consequences are considered from the point of view of effect on the next up and below in the hierarchy of activities and on the overall objective of the system as noted in [7]. It is assumed that no control is in place in the system and prioritization is not considered

Double rod-double acting cylinder (1), Shut-off valve (2), Flexible connection (3), Pressure gauge (4), Gas accumulator (5), Position directional control valve (6), In-line Filter(8), Variable flow control valve(10), Directional Control Valve(11), Pressure relief valve (12), Hydraulic motor (13), Generator (14), Reservoir(15), Load pressure control valve (16), Check valve (17), Oil tank (18), Hydraulic pump (19), Directional control valve (20), Non Compensate flow valve(22)

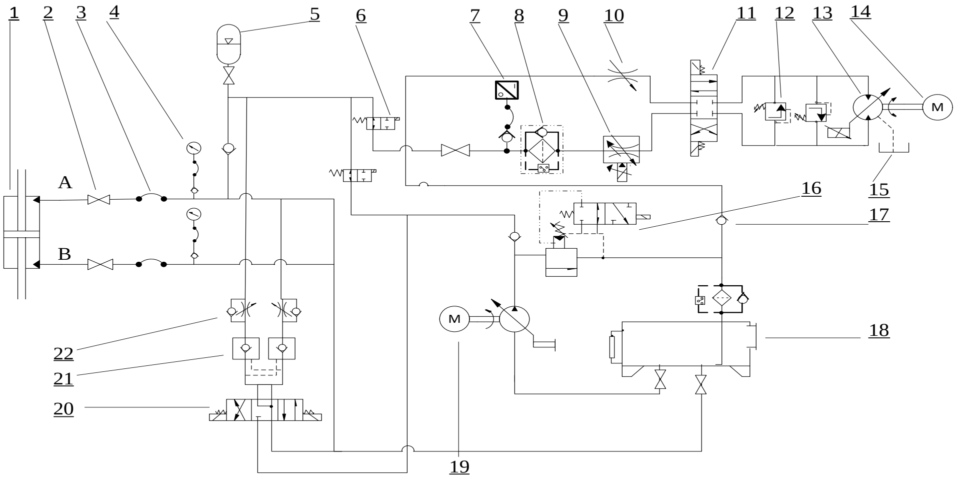

Fig 5.Schematic diagram of Hydraulic PTO based on ISO 1219

Table III FFMEA SHEET

Sub system/Components	**Function**	**Failure Mode**	**Failure Consequences**	**What to monitor**
1) Structure • Connection Joint • Floater • Arm • Kinematic	Transfers required linear and angular motions (displacements and velocities) between Floater and Hydraulic cylinder	Seizure of movements Low efficiency of motion transfer	Hydraulic cylinder fails to deliver fluid at required pressure Floater fails to generate wave to interfere destructively with sea-wave jeopardizing chances of utmost abstraction Production of electricity is seriously jeopardized	Crack at joints Monitor degradation of floater Monitor Crack at rod-arm joints Strain and stresses at arm-rod joint
2) Hydraulic Cylinder (double rod) [11] • Rod, barrel, • Seals (Rod seal, Static seal, and wiper seal)	Convert energy in pressurized hydraulic fluid into reciprocating motion of the rod	Low efficiency of conversion due to hydraulic power loss during conversion. Failure of conversion (due to seizure, etc.) Likely causes: Fatigue, buckling of piston rod, leakages from worn out bores and broken seals	Reduced discharge to the lines (Low volumetric efficiency) Overheating of motor causing loss of lubrication, wear, leakages and damage Environmental contamination from leakage	Temperature Pressure Temperature of coolant
3) Pipeline-fluid subsystem • High pressure Lines, • Low pressure lines, • Shut-off valves, • Check valves, • Pilot-to-open and Close operated check valve, • Variable • Flow control valve, • Accumulators, • Pressure relief valves, • Directional control valve, • Filter, • Hydraulic fluid	Control and maintain flow of energized clean hydraulic fluid at designed pressures and rate through the right directions when desired from the hydraulic cylinder to the motor, reservoir and back the hydraulic cylinder	Loss of control Loss of flow energy Unsteady discharge of fluid Low discharge More discharge Fluid flow in wrong direction No discharge of fluid High temperature of fluid Contaminated fluid	Overloading Line could burst leakage and environmental pollution. Low discharge causes motor overlabour and damage. Vibration due to Unsteady discharge, pressure pulsation and transient pressure spike causes loosened connections and joints, misalignment, Leakages, and environmental pollution. Overheating causes loss of oil lubrication, increases rate of wear, low motor efficiency, and low generator output. Loss of systems control leads to catastrophic system failure. No discharge at cylinder or motor; might cause damage. Blockages cause sudden pressure build up in pressure lines leading to burst of pipe and/or hose and damage to other components Leakages of oil causes severe environmental consequence. Objectionable noise, induced vibration with eminent system collapse. Drop in electricity generation capacity. Contamination of hydraulic fluid resulting to clogging and heavy wear of sliding surfaces e.g., of valve	Vibration, Internal pressure Line pressure Flow discharge Flow directions Monitor fluid temperature Monitor colour change

Sub system/Components	Function	Failure Mode	Failure Consequences	What to monitor
4) Hydraulic motor	Converts hydraulic energy of the fluid to rotational energy of the shaft	Low efficiency of conversion due to losses in the motor, low fluid energy flow. Unsteady conversion No conversion taking place	Low shaft torque No shaft torque No power generation Unsteady or intermittent High temperature Vibration and noise	Flow, head and power measurements
5) Electric generator (induction machine)	Generate electricity power through actions of rotating shaft across lines of flux of an electromagnet	Opening or shorting of circuit winding. Abnormal connection of stator windings Rotor dynamic eccentricity Broken rotor bars Cracked end rings Static and dynamic air-gap flux and phase currents Increases in torque pulsations Decreases in average torque Higher losses, and reduced efficiency	No conversion Reduced efficiency of conversion Intermittent conversion	Roller bearing and winding temperature[12-14] displacement monitoring, roller bearing and gearbox vibration, shaft vibration, stator and rotor currents[15], power spectrum monitoring [14], shaft flux and axial leakage flux
6) Oil reservoir	Receptacle for expended fluid from hydraulic motor. Heat exchanger	Leakage, overheating [16] , Contamination	Shortage of fluid Loss of lubrication	Oil temperature, oil level

Table IV HAZOP SHEET

Component	Design intent	Guide word	Deviations	Possible Cause	Consequences
1. Wave	To continuously excite the floater with a torque τ_{ext}	No	No excitation	Calm sea	No pressure developed in the cylinder
		Less	Low excitation	Calm sea	Low pressure developed in the cylinder
		More	High excitation	Turbulent sea state	Dangerous pressure developed in the cylinder
2. Float/Arm	To continuously oscillate at a height that displaces kinematic arm through θ_{arm} radians and at angular velocity of ω_{arm} rad/s	No	Oscillation/No	Calm sea state	No power developed in the cylinder
		slower	Oscillation /Slow		Less power developed in the cylinder
		Fast	Oscillation/Fast	Turbulent sea state	Dangerous pressure develops in the cylinder; could result to burst
3. Kinematics	To continuously transmit a resistive torque of τ_{PTO} at every floater oscillation thereby enhancing the capacity to optimize absorption of wave energy To continuously transmit stroke X_c due to θ_{arm} the cylinder rod at velocity of V_c	No	Transmit resistive torque τ_{PTO} /No	link broken Totally	No power developed in the cylinder
		Less	Transmit resistive torque τ_{PTO} /Less	Link partially broken	Less power developed in the cylinder
		More	Transmit resistive torque τ_{PTO} /More	Turbulent sea state	Dangerous pressure develops in the cylinder; could result to burst
		No	Transmit speed/No	link broken Totally	No absorption of wave energy
		Less	Transmit speed/Less	Link partially broken	Partial absorption of wave energy
		More	Transmit speed/More	Turbulent sea state	Buckling of double acting rod Failure of links and/or mechanisms Over pressurised lines
4. Hydraulic Cylinder	Develops force F_c due to interaction of fluid and rod movement and transmit it to the kinematics Develop line pressure $P_{A,}$ and P_B in chambers A and B respectively due to X_c and V_c , and pump it to hydraulic motor Suck in oil at flow rate $Q_{A,}$ and $Q_{B,}$ through A and B respectively	More	Cylinder Pressure $P_A, P_{B,}$ /More	Turbulent sea state	Burst of cylinder Buckling of rod Over pressurised lines
		Low	Cylinder Pressure $P_A, P_{B,}$ /Low	Calm weather	Low cylinder force Slow oscillation Slow flow through pressure lines
		No	Cylinder Pressure $P_A, P_{B,}$ /No	Calm sea state No cylinder force	No flow No motion
		Slower	Rod velocity/slower	Calm sea state No cylinder force	Low cylinder force Slow oscillation Slow flow through pressure lines
		Faster	Rod velocity/Faster	Turbulent sea state	Fast flow through ports High cylinder pressures at both chambers
		Fail	Rod movement/Fail	Buckling due to Turbulent sea state Rod got hooked	No work done on fluid, no fluid pressure thus no energy generation
		More	Flow rate $Q_{A,}$, $Q_{B,}$ /More	Turbulent sea state	Overload the pipeline with potential burst of pipe Leaked fluid causes environmental pollution

Component	**Design intent**	**Guide word**	**Deviations**	**Possible Cause**	**Consequences**
4. Hydraulic Cylinder(*continued*)		Low	Flow rate $Q_{A,}$, $Q_{B,}$ /Low	Calm sea state Partially broken links	Low flow energy of fluid leading to no or low work done on the turbines and low energy output
		No	Flow rate $Q_{A,}$, $Q_{B,}$ /No	No work done on cylinder fluid due to; total broken links, calm sea state	No electricity generation
5. Variable displacement Bi-directional Hydraulic motor	Develop torque $\tau_{M,}$ due to $P_{A,}$ and P_B to drive the generator a variable displacement function controls these pressures and flows $Q_{A,}$ and $Q_{B,}$	No	Displacement /No	Line blockage Low energy fluid	Damage of motor No torque
		No	Torque/No	No displacement due to; Line blockage Low energy fluid	No current
		More	Torque/More	Turbulent sea state	Twist of shaft Increased current
		Less	Torque/Less	Low pressure of incoming fluid due to; Leakages Calm sea-state Partial broken links of rod	Low current
		Fluctuation	Torque /Fluctuation	Partial blocked line Pressure pulsation due to dynamics of fluid in pipe	Fluctuation in current
		Slower	Rotation /slower	Low flow energy fluid due to partially blocked lines, leakage of line, buckled rod, partially broken	Low voltage current
		Faster	Rotation /faster	Over pressurized lines due to Turbulent sea state	High voltage current
		Fail	Bi-directional / Fail	Faulty pump	Power loss
6. Generator	• Produces electric current from the interaction between rotating shaft and system of coils	More	Current /More	Turbulent sea state	System overload
		Less	Current/Less	Low flow energy	Loss of efficiency
		No	Current/No	No/less flow in the lines	Loss of objective Loss of reputation
		Fluctuation	Current /Fluctuation	Loss of bi-directional function	Loss of efficiency
7. Hydraulic Oil tank	Hydraulic oil used to produce $\tau_{M,}$ is held in the tank temporarily for heat exchange after which it is returned to the hydraulic cylinder via return line	Less	Tank oil/Less	Minor Leakage in the system	Air in lines Loss of efficiency Maloperation of hydraulic cylinder
		No	Tank oil/No	Major Leakage in the system	Air drawn into pumps Damage of motor
			Out Flow /No	Exit port blocked No oil	Flow stops Over pressurising of tank leading to burst

Component	**Design intent**	**Guide word**	**Deviations**	**Possible Cause**	**Consequences**
			In flow/No	Entrance port blocked No oil in circulation	Overpressure and possible burst of return line Damage of motor
		Slow	Heat exchange/slow	NA	Fluid temperature rises
		Reverse/back	Return lines pressure/reverse	Less oil in the tank	No flow to the cylinder
		Low	Temperature/low	Extreme weather	Fluid congeals No/sluggish flow in pipes
		More	Temperature/more	External condition	Hydraulic oil loses composition
8. Pressure Line	Leads high pressure oil from the cylinder to the hydraulic motor.	Fail	Flow/Fail	No fluid ; fluid has all leaked away Hydraulic cylinder not functioning, Congealed oil from extreme cold weather, blocked valve	No flow to the hydraulic motor may damage the motor Generation of electricity is botched
		Fluctuation	Flow/ Fluctuation	Faulty flow valve Partial blockage of lines	Unsteady discharge Power lost at motor Vibration could cause misalignment and further complicate problems
		Other	Flow/Other	Leakage caused by corrosion pitting	Fluid drain Environmental pollution
		Less	Rate/Less	Fluid shortage due to leak	Drop in torque produced by motor
		More	Rate/More	Failed accumulator and control	Overload on pipeline and motor; Failure of pipeline
9. Return Line	Returns used oil to the tank/reservoir	Fail	Flow/Fail	Blockage(closed valve or debris) No fluid	Overloading of motor Failure of motor Overheating of motor
		Fluctuation	Flow/ Fluctuation	Valve failure	Vibration
		Other	Flow/Other	Leakage caused by corrosion	Drop in fluid level Environmental pollution
		Less	Rate/Less	Valve failure Blockage of line	Time wastage, Reduced efficiency
10. Fluid	Conveys power in a hydraulic circuit. Act as lubricants in valves and components it passes through reducing friction and reducing metal to metal contact Form seal in conjunction with fine machining of spools	Fail	Surfaces separation / Fail	Loss of viscosity due to high temperature. Contamination	Increases rate of abrasion and wear of touching surfaces
		Other	Flow/corrodes pipeline	Contamination	Loss of containment Environmental pollution Aeration of the hydraulic circuit
		As well as	Fluid is contaminated	Infiltrations by seawater, biofouling etc.	Blockages, wear, increased rate of corrosion, erosion,

IV. DISCUSSION AND CONCLUSION

Wave Energy Converters produces electrical power from sea-wave energy based on principle of conservation of energy. This work, concerns with the aspect of robust design which is currently challenged by lack of failure data using safety studies. FFMEA and HAZOP analysis were conducted for such WEC with hydraulic PTO to support initial design decisions and later possible redesign and/or maintenance decision at operation stage respectively. The system is decomposed to components and subsystems level enough to make detailed identification of potential functional failures possible and their respective consequences on the overall system objectives thoroughly analysed. From the study of relevant literatures, majority of the identified Failure Modes are related to fluid; lack of appropriate properties of temperature and viscosity and/or incursion of contaminants. Consequences range from low output, high cost of intervention action, and system collapse.

References

[1] Ericson, C. A. (2005), *Hazard Analysis Techniques for System Safety,* John Wiley and Son, Fredericksbury, Virginia.

[2] Nivolianitou, Z., Konstandinidou, M. and Michalis, C. (2006), "Statistical analysis of major accidents in petrochemical industry notified to the major accident reporting system (MARS)", *Journal of hazardous materials,* vol. 137, no. 1, pp. 1-7.

[3] Mueller, M. and Wallace, R. (2008), "Enabling science and technology for marine renewable energy", *Energy Policy,* vol. 36, no. 12, pp. 4376-4382.

[4] Pacific Gas and Electric Company (2010), *Wave Energy Converters (WECs),* available at: http://www.pge.com/includes/docs/pdfs/shared/environment/pge/waveconnect/wave_energy_converters.pdf. (accessed 12/16).

[5] Det Norske Veritas, (2005), *Guidelines on Design and Operation of Wave Energy Converters; A guide to assessment and application of engineering standards and recommended practices for wave energy conversion devices*, Carbon Trust, London, UK.

[6] Budal, K. and Falnes, J. (1975), "A resonant point absorber of ocean-wave power", *Nature,* vol. 256, pp. 478-479 [With Corrigendum in vol 257, p. 626].

[7] Stamatis, D. H. (2003), *Failure mode and Effect Analysis: FMEA form theory to execution,* 2nd ed, Quality Press, Wisconsin, USA.

[8] BS IEC 61882 (2001), *Hazard and operability studies-Application guide,* BS IEC 61882, British standard.

[9] Henderson, R. (2006), " Design, Simulation, and Testing of a Novel Hydraulic Power Take-off System for the Pelamis Wave Energy Converter ", *Renewable Energy,* vol. 31, no. 2, pp. 271-283.

[10] Hansen, R. H., Kramer, M. M. and Vidal, E. (2013), "Discrete Displacement Hydraulic Power Take-Off System for the Wavestar Wave Energy Converter", *Energies,* vol. 6, no. 8, pp. 4001-4044.

[11] Hitchcox, A. (22 November, 2014), *A look at Hydraulic Hose Failures,* available at: http://hydraulicspneumatics.com/blog/look-hydraulic-hose-failures (accessed 30 November, 2014).

[12] Gellermann, T. (2012), "Extension of the scope of Condition Monitoring Systems for multi-MW and offshore wind turbines", *VDI-Conference Schwingungen von Windenergieanlagen,* 7-8 February, Bremen, Allianz Risk Consulting GmbH., Germany, .

[13] Kelly, J., Wright, W., O'Sullivan, D. and Lewis, A. (2013), "A study: Potential supervisory Real Time Integrated Monitoring and Control System (RTIMCS) solutions for wave energy converters", *European Wave and Tidal Energy Conference (EWEC),* 2-5 September,2013, Aalborg, Denmark, Irish Research Council, .

[14] Hunter, D. J., Tavner, P. J., Ward, D. M. and Benaragma, D. (1982), " Measurements of the harmonic components of instantaneous electrical power delivered at the terminals of a 500 MW turbogenerator", *International Conference of Sources and Effects of Power System Disturbance,* Vol. 3, London, UK, IET, .

[15] Tavner, P., Ran, L., Penman, J. and Sedding, H., (2008), *Condition Monitoring of Rotating Electrical Machines,* Institution of Engineering and Technology.

[16] Kelly, J., O'Sullivan, Wright, W. M. D., Alcorn, R. and Lewis, A. W. (2014), "Challenges and Lessons Learned in the Deployment of an Offshore Oscillating Water Column", *COMPEL-The international journal for computational and mathematics in electrical and electroic engineering,* vol. 33, no. 5, pp. 1678-1704.