A study: Potential supervisory Real Time Integrated Monitoring and Control System (RTIMCS) solutions for wave energy converters

James Kelly*[1], William M. D. Wright[2], Dara O'Sullivan#[3] A. W. Lewis[4]

[1,4] *Beaufort Research-Hydraulic and Maritime Research Centre, University College Cork*
Cork, Ireland
*james.kelly@ucc.ie
[1,2] *Department of Electrical and Electronic Engineering, University College Cork*
College Road, Cork, Ireland
[3] *Analog Devices, Inc.*
Airport Business Park, Cork, Ireland
Formally of Hydraulic and Maritime Research Centre,
University College Cork
Cork, Ireland

Abstract— **The increased demand for clean renewable sources of electricity generation has helped foster strong growth in ocean energy development in recent years. In the area of Real-Time Integrated Monitoring and Control Systems (RTIMCS), the focus of most developments has been in Power Take-Off (PTO) and generator control, while the supervisorymonitoring and control aspect of RTIMCS have been largely ignored. This paper presents some of the high level RTIMCS supervisoryconcepts, necessary components, their importance, and how they might benefit the wave energy converters.**

***Keywords*— Ocean energy, Wave Energy Converts, real time integrated monitoring and control systems, condition monitoring, supervisory control, operation and maintenance**

I. INTRODUCTION

In the field of renewable energy, ocean wave energy technology has historically struggled to break through to commercial implementation, but recent years have begun to see a maturing of some technologies, with several companies now conducting sea trials with fractional-scale and full-scale prototypes.

During this maturing process, control system research and development's main focus has been on power take-off (PTO) methods forcontrol and efficiency, examples of this can be seen in [1]-[4].However, all electricity producing power plants, from wind, to nuclear, to fossil fuelare run by sophisticated, comprehensive Real-Time Integrated Monitoring and Control Systems (RTIMCS) that allow both for total control of the energy output, which could be classified as the PTO, of the plant and the monitoring of the health of the plant's major and minor components. Each power plant has system requirements unique to the particular methods in which it generates electricity, and therefore a unique RTIMCS scheme is necessary for a given plant. As the ocean energy sector begins to emerge from the research and development stages to become a commercially viable energy solution, wave energy converters (WEC) and the like will require their own robust supervisory control and monitoring system that can address the unique needs and challenges that generating electricity in an off shore environment presents. However, there has currently been little investigation into this area of RTIMCS for WECs.

Because WECs are relativity small, unmanned power plants that are located in corrosive, unforgiving, and often violent environments, the demands of the RTIMCS for WECs will, in many ways, be much more complex than thoseof conventional plants or even onshore wind turbines. The environment in which WECs exist and the inability to schedule and carry out regular maintenance inspections of offshore devices places extra significance on the RTIMCS ability to monitor the overall health of the plant. Also, the complexity of controlling an array of WECs in an open loop environment suggests that a highly intelligent and automated control system will be necessary to maximise both system output and operational life expectancy. This paper pulls knowledge from well-documented RTIMCS of wind turbines as well as more conventional fossil fuel and nuclear power plants andavailable condition monitoring sensors and related equipment are presented. Because of the open loop nature of WECs, the paper will also present various forms of outside data streams, including information regarding waves, weather, and grid, how it can be incorporated into the RTIMCS for WECs, and the benefits expected from using outside data with the plant controls. The available overall control schemes that effect both decision making and data transfer methods are examined with the ultimate goal of WEC arrays in mind: i.e. centralised master-slave (MS) schemes common to programmable logic controllers (PLC) and decentralised schemes common in distributed control systems (DCS). The ultimate goal of this paper is to serve as a baseline for the development of the supervisory elements RTIMCS for ocean energy converters.

II. CONDITION MONITORING

Many of the challenges facing the maturing ocean energy sector are very similar to those that face the wind energy sector, particularly off shore wind turbines. Because of the environment that both off shore wind and ocean energy devices reside in, a robust condition monitor system will be necessary to help minimize operation and maintenance (O&M) costs during the lifetime of any device. A study done in 2006 stated that for a 20-year lifetime of 750 kW onshore wind turbinesthe O&M costs can be upwards of 25%-30% of the total energy generation costs [5]. O&M costs for devices located at sea can be expected to be higher because of difficulties related to device access as well as the harsh nature of the environment that the devices would be deployed in. The ability of the control system to accurately monitor the various subsystems found in an ocean energy converter will be paramount to maintaining good cost efficiency and maximizing device lifetime. In this section the various system monitoring sensors will be broken down and described in greater detail in order to layout what would be necessary in the condition monitoring role of a control system for an ocean energy converter. Because of similarities between wind and ocean energy conversion, this section will rely heavily on the advances that have already been made in condition monitoring within the wind energy sector.

Any condition monitoring system that would be implemented within an ocean energy converter will require the latest developments in early fault detection in any and all subsystems of that converter. If faults can be discovered in their early stages, maintenance trips can be scheduled around the necessary weather windows before complete failure, thereby minimizing both cost and loss of revenue due to unscheduled down time. The typical subsystems that are present in an ocean energy converter include: an induction machine as a generator, a power take-off (PTO) system, which can include but are not limited to, components such as hydraulic systems, air turbines, driving rods, drive shafts and couplings, gearboxes, power electronics, and general device structures such as containment units. The equipment required for monitoring these different subsystems themselves include: vibration sensors; acoustic emission sensors; current and voltage meters; and temperature sensors. The data gathered by such equipment must then be properly recorded and analysed through various methods which best compliment the monitoring device, such as fast Fourier transforms, wavelet transforms, and hidden Markov models to name a few [6].

A. Vibration

Vibration sensors have long been applicable and trustworthy monitoring devices in both traditional and renewable energy plants alike for a large variety of uses. Vibration sensor types are dependent on the frequency range of the relevant system that is being monitored: position transducers for low frequency, velocity sensors for mid-frequency, and accelerometers for high frequency [7]. Within typical wind energy conversion systems, vibration sensors are most commonly used for gearbox and bearing monitoring and diagnostics [7], [8].Both gearbox and bearing monitoring techniques used in the wind energy sector can be carried over and applied to the ocean energy sector as well.

One example of equipment that is often monitored using vibration sensors is roller bearings used in turbine drive shafts. Vibration analysis is often performed here by looking at the frequency spectrausing fast Fourier transforms (FFT) to separate vibrations caused by normal operation of rolling bearings and vibrations caused by damaged bearings. Damaged bearings cause small vibrations within the housing of the bearing, the frequency of which is dependent on both the revolution of the shaft the bearing is supporting and the type for bearing being used. This knowledge combined with the FFT of the vibrations measured can be used to find which part of the bearing has been damaged. Also, advances have shown that wavelet neural networkanalysis of vibration signals can be used in place of FFTs [9].

Recent studies using advances in Discrete Wavelet Transform (DWT) have also shown that vibration monitoring can also be used outside of bearing and gearbox condition monitoring. Cracked rotor bars within an induction machine cause core vibrations in the axial direction on the shaft of the generator. Using a vibration sensor combined with DWT, such cracks can be detected early before they can cause major problems within the induction machine [10].

While vibrations sensors are typically well tested, reliable, and even standardized, they still are not without disadvantages and limitations. Vibration sensors have shown limited success in early fault detection in low speed bearings and gearboxes, and a study done on remote condition monitoring for Vestas turbines showed that several vibration monitoring systems caused a flood of both numerous alarms related to a single fault and false alarms cause by transient vibrations [8]. In many instances these limitations can be overcome using Acoustic Emission (AE) monitoring rather than typical vibration monitoring.

B. Acoustic Emissions

Acoustic emissionsusually occur when an applied external stress produces transient elastic waves via localised stress relief and material deformation, often in the form of slipping of grain boundaries, plastic deformation and crack propagation. [11].However, any event that produces a similar acoustic event, such as frictional wear, bearing damage or machinery vibration, may be similarly monitored. Passive AE monitoring is used when the AE events are produced as a by-productof the operation of the structure; active AE is used when additional stress is deliberately applied with the sole intention of producing AE events to interrogate a structure. Most AE monitoring is passive.

Passive AE based condition monitoring has a wide variety of uses. As stated previously, they can be substituted for vibration sensors, particularly in the roller bearings of slower rotating drive shafts. AE analysis has been shown to detect some faults earlier than more typical vibration analysis [12]. Along with being used for early fault detection in roller bearings, AE can also be used to monitor faulty bolts and even loose bolts in low-speed rotating machinery [13]. Early fault detection on such components on a device deployed at sea could be very useful information during maintenance trips, as they could save time during inspection and help to prevent larger problems if they can be detected and repaired before they cause greater damage. Active AE can be used to find damage such as crack propagation in drive shafts, turbine blades, support structures and welds, and such information can lead to fatigue life prediction [6], [14], [15].

AE sensors are typically less intrusive than are vibration sensors and are more easily attached to the components that they are monitoring [6], [8]. While they are very flexible and can be used for early fault detection, AE sensors systems are much more expensive to implement then are vibration sensors. Because of the high frequency signals that are used in AE monitoring, very high data sampling rates are required and the high rate of sampling leads to large data storage requirements [8]. There are two typical modes of AE emission monitoring; discrete pulse counting, and continuous energy or frequency monitoring. Both of these can be compatible with typical system controllers such as PLCs, as the output from the AE sensor system can be a simple AE counter or mean frequency value.

C. Temperature

Temperature monitoring has long been part of condition monitoring systems for power generation plants and electrical machines alike. Within ocean energy converters, temperature sensors can be deployed in places like induction machines, power electronics, mechanical breaks, and hydraulic, lubricating, and cooling oil.

Induction machines normally include several temperature sensors that are imbedded within the device during manufacturing. There are three common approaches for induction machine temperature monitoring: local point monitoring using embedded sensors, distributed monitoring using the temperatures of coolant fluids, and thermal imaging [16].Local point embedded sensors, typically resistance temperature detectors (RTD) or thermocouples, are most often used to monitor the temperature of the three stator windings of the induction machine. Such measurements are universally used for condition monitoring of induction machines.

RTDs and thermocouples are also often used to monitor the temperature of the roller bearings of the induction machine where are they mounted direction to the bearing housing. For machines of the size considered for this paper, 100 kW to 2 MW, distributed temperature monitoring and thermal imaging are not commonly used, however monitoring the temperature of any oil used specifically for cooling purposes can be classified as distributed temperature monitoring.

All hydraulic systems used in an ocean energy converter will require, at the minimum, that the oil reservoir temperature be monitored at all times. Should the oil overheat, the properties of the oil may become compromised and lead to a failure of the hydraulic system. By monitoring the oil temperature, the system can be shut down if necessary before overheating can occur thereby prevented system failure, as was demonstrated in [17].

Temperature monitoring of power electronics is much less straightforward but still an important aspect of condition monitoring for ocean energy converters. Most failures of semiconductor based power electronics have a thermal aspect, and they are typically found in the bonding wires and solder layers of the circuit board [18]. The interface connections of power electronic systems that are most like to break down due to stress caused by thermal cycling cannot be easily accessed. Because of the difficulty in direct thermal monitoring of power electronics, physical models have been developed that can respond to both environmental and load cycling. Such models have been applied to PWM power electronics, and real-time modelling estimates have shown excellent agreement with real-time temperature measurements during experimentation [19].

D. Current, Power and Flux

The three most common areas for faults in induction machines are the bearings (40%), the stator (38%), and the rotor (10%) [20]. Stator and rotor faults include opening or shorting of circuit windings, abnormal connection of stator winding, dynamic eccentricity, broken rotor bars and cracked end rings, and static and dynamic air-gap eccentricities.They can lead to unbalances and harmonics in the air-gap flux and phase currents, increases in torque pulsations, decreases in average torque, higher losses, and reduced efficiency [8].

The mechanical and electrical stresses that are constantly exerted on the stator and rotor make them prone to faults that tend to develop over long periods of time. The nature of these faults along with the general inaccessibility of the stator and more acutely the rotor have lead to the development of more sophisticated means of induction machine monitoring. The monitoring of both stator and rotor currents can be used to discover both mechanical and electrical faults within the rotor; this method is described in [16]. Studies have shown that monitoring the power spectrum of an induction machine can also be an effective method for detecting rotor damage [21], [22]. Shaft flux and axial leakage flux monitoring can lead to the discovery of faults in squirrel cage induction generators (SCIG) including loss of phase, inter-turn short circuits, broken rotor bars and negative phase sequencing [16].

III. OUTSIDE VARIABLES

Conventional electrical power plants exist in a nearly completely enclosed environment. The only variable in a conventional system that is not under the control of the system is the load, which is dictated by the grid that it is connected to. To adjust to changes in loading, conventional power plans can simply increase or decrease the amount of fuel being used to match the load requirements of the grid. Ocean energy converters by contrast exist in an open system and have many uncontrollable variables that directly affect the system. The more information about those variables that can be fed into the control system of the ocean energy converter and the more accurate that information is, the more efficiently the device can operate.

Some outside variables that can directly impact an ocean energy device include weather conditions, wave conditions, and grid load. All three of these variables have systems that can give live real time conditions and also can be predicted minutes, hours and even days in advance. Changes to all of these outside variables often force changes in the control laws that govern the behaviour of an ocean energy converter. This section reviews some of the latest technology and data available for monitoring as well as predicting the conditions of these three variables as they affect ocean energy converters.

A. *Wave Monitoring*

One advantage that the wave energy generation sector has over the wind sector is that wave climates can be more accurately predicted in both the short and medium term than can wind. This enables better power production estimates that can minimize penalties from the grid for missing targets and can also benefit grid operators and other more conventional power producing plants. This section and the following will give examples of short and medium term prediction and monitoring that is available today.

1) Surface Buoys: The use of surface buoys for single point wave measurement has been common and widespread in numerous ocean engineering and oceanographic fields for years. The most common type of surfaces buoys for wave measurement are Particle Following and Pitch-Roll-Heave buoys. They are typically small and easily deployed and recovered, allowing for a low cost means of sea surface monitoring [23]. Three common makes of particle following surface buoys are the Waverider, the Seawatch Mini II, and the Triaxys, and common makes of pitch-roll-heave buoys included the Wavescan and the NDBC three meter discus buoy.Fig. 1showsa Wavescan buoy that was deployed at a depth of 100m off Belmullet, Co. Mayo, Ireland, and a Waverider buoy that was deployed in Galway Bay, Ireland.

Fig. 1 Wavescan, Belmullet, Ireland (Left), Waverider, Galway Bay, Ireland (Right)

Particle following buoys obtain wave measurements based on the simple assumption that they replicate the profile of the passing waves as they float on the sea surface. The surface elevation is measured using an accelerometer that is found within the buoy; the relevant wave data is established through Fourier analysis. For real-time data collected by the Waverider buoy, 8 spectra of 200-second intervals each are collected over a 30-minute period. At the end of each 30-minute period, the necessary calculations are executed and the resulting file is transmitted; the datatransmitted includes significant wave height, significant wave period, wave direction, and maximum wave height [24].The accuracy of the data collected by particle following buoys has been proven by multiple studies including those carried out in [25]-[27].

More recent developments in surface buoys include the incorporation of GPS for wave measurements. The GPS uses the Doppler principle; the signals sent from the buoy to the satellite has a Doppler shift caused by the movements of the buoy in the sea. The GPS buoys have shown excellent performance in the field, can measure longer wave periods than their predecessors, and are shown to be more robust, though they have shown some difficulty in higher seas when connection to the satellite can be compromised [8].

2) Acoustic Doppler Current Profiler: The Acoustic Doppler Current Profilers (ADCP) measure pressure and orbital velocities of passing waves as well as residual ocean currents through Doppler sonar techniques and have been a trusted measurement tool in the marine sector for decades. ADCPs are typically mounted on the sea floor with 4 acoustic beams facing upward at 20-30 degree angles and oriented at 90 degrees in azimuth. They can be deployed autonomously, cabled to shore or device, or cabled to a surface buoy, but to be useful in RTIMCS, an ADCP would have to be cabled to shore or a buoy to allow for real time acquisition of data; Fig. 2 shows a typically ADCP.

Fig. 2 Acoustic Doppler Current Profiler with 4 transducers

The data collected by ADCPs has shown excellent agreement with data collected by surface buoys [29]-[31]. The acquisition time for accurate wave data is 15-30 minutes, which is similar to the acquisition time necessary for surface buoys [32]. Because they are mounted on the sea floor, they are less susceptible to damage from harsh conditions typically found at sea than are their surface buoy counterparts. However, the deeper the deployment depth, the more difficult and costly it is to deploy and service the APDC, and while biofouling of the device decreases with water depth, the accuracy of the ADCP similarly decreases [32].

3) High Frequency Radar: One more recent development in wave monitoring that has potential to be useful in marine renewable applications is High Frequency (HF) radar systems. Examples of HF radar systems included the WERA [33] and SeaSnode [34]. The radar systems are a shore based remote sensing systems that can monitor wave, current and weather conditions using short wave radar technology [33]. The WERA system operates a frequency modulated continuous wave mode, which transmits a continuously swept, low power RF-signal. The system requires two arrays of antenna, one of the transmission signals (Tx) and one to act as the receiver (Rx). A minimum of two HF-radar systems are required to obtain practical accurate data.

One benefit of the HF radar systems is the high spatial variability. The radar systems are used to produce maps of wave data, which can cover several square kilometres of ocean, rather than single point measurement that is common with ADCPs and wave rider buoys. The data is made up from the directional spectrum of the radar, which can be partitioned into wind wave and swell components in different directions and frequency bands. The spectrum can be used to calculate basic wave parameters including significant waveheight, wave direction, and mean and peak period. From these measurements, wave power and energy period can also be calculated [35].Fig. 2 and fig. 3, taken from [35], show wave power and period respectively from the Wave Hub test site off the cost of Cornwall, UK. This information,combined with the spatial variability of the data, can be used both to set the control laws of an operational WEC as well as to predict with some certainty the expected power output of a given device.

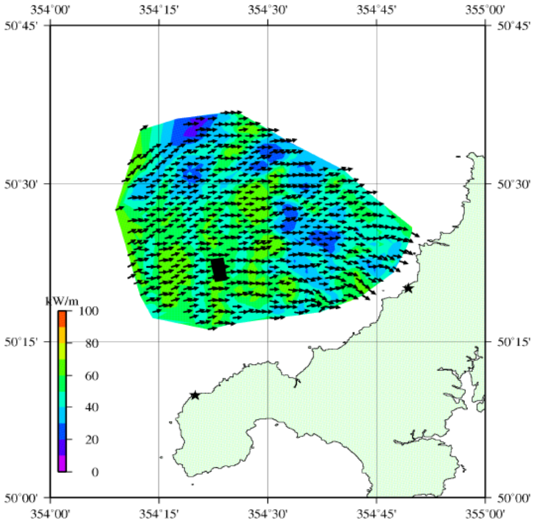

Fig. 2 Wave Power and Direction, Wave Hub Site, Cornwall, UK, 31 March, 2011 [35]

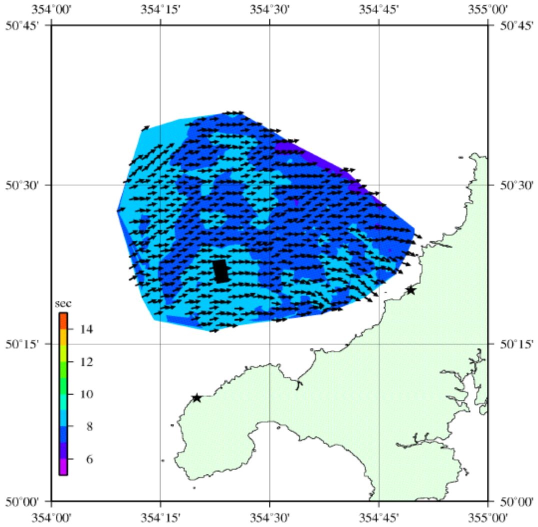

Fig. 3Wave Period and Direction, Wave Hub Site, Cornwall, UK, 31 March, 2011 [35]

The antennaarrays for an HF radar system are set up on shore near the site that is to be monitored. Because the entire system is located on shore, the system can be much more easily monitored and maintained. Fig. 3showsRx antenna of a WERA system installed along Dingle Bay, Co. Kerry, Ireland from November, 2012. The WERA system was compared to more traditional sensors, ADCP and wave rider buoys and showed excellent agreement with those sensors [36].

Fig. 4 WERA Rx Antenna, Dingle Bay, Co. Kerry November, 2012

B. *Medium Term Wave and Weather Forecasts*

The unpredictability of renewable electricity producers like wind and wave energy converters has long been a major concern of electrical grid operators. Medium term wave forecasting refers to the forecasting of wave conditions from a few hours up to 5-7 days into the future. The integration of accurate wave forecasting into the control systems of wave energy converters could be greatly beneficial to both WEC operators and grid operators alike. It will allow for the devices to estimate their power production and relay those predictions to grid operators, minimizing premium prices and penalties incurred by missing estimates and maximising grid reliability. The benefits that directly affect the WECs themselves include control, operation, and maintenance strategy, allowing for the scheduling of repairs, the maximising of output potential, and storm protection preparation.

Medium term forecasting is weather dependant, as wind and general weather systemsalong with ground swell all affect wave conditions. Most forecasting is currently preformed by organizations like NOAA or the Irish Marine Institute using computer models and software such as SWAN and MIKE21. Such models have clearly shown accuracy as far as 48 hours in advance, even under periods of rapidly changing sea state conditions [37]. A study performed in [38] has shown that wave parameters including significant wave height and period can be accurately predicted and used to estimate power production for several different types of WECs at the Hanstholm site in Denmark.

C. *Smart Grid*

The term “Smart Grid” is used to describe a variety of recent advances in the movement to allow two-way communication before energy consumers and producers [39]. Advance metering at the consumer end is the most commonly known aspect of smart grid design, but it also has uses in distribution automation (DA) and distributed energy resources (DER). DER are small sources of generation that are connected the distribution system, but have levels of penetration typically below 15% of the peak demand [40]. Any singular wind or wave farm on a strong grid could be characterised as DER.The use of smart grid communication between devices, farms, and the main grid will be important for both the generators and the grid monitors, and it should allow for a more robust grid, while minimising of load sheddingfrom renewable energy sources and still maintaining good power quality.

IV. CONTROL STRATEGY OPTIONS

There are two basic strategies that are utilized for electrical plant control: Master-slave control systems (MS) and distributed control systems (DCS). Both will be briefly introduced in this section along with their potential use for control of WECs with farms.

A. *Master-Slave Control Systems*

Master-Slave systems have been widely used since they were first developed in the 1960’s [41]. Today they are common in wind farm control and as well as other areas of renewable energy generation. MS supervisory command and data acquisition (SCADA) is combined with distributed databases local to devices within the farm for real-time monitoring and control of devices of a wind farm [42].

MS systems have a centralized master control unit that allows monitoring and control of the entire system to run though the single centralized controller. The control of the slaves is done through the master via a communication network that links all the devices in the system. Slaves on such a network only transmit information when polled by the master. The amount of data that can be transmitted is limited by the bandwidth of the communication network. The limit on the bandwidth can become problematic as the number of devices within a system increases, such as the every larger size of today’s wind farms. Control methods and improvements to MS systems are constantly being investigated and developed to minimise the impact of such burdens on the ever growing wind farm networks [43]. Fig. 5 shows a graphical example of a master-slave control system.

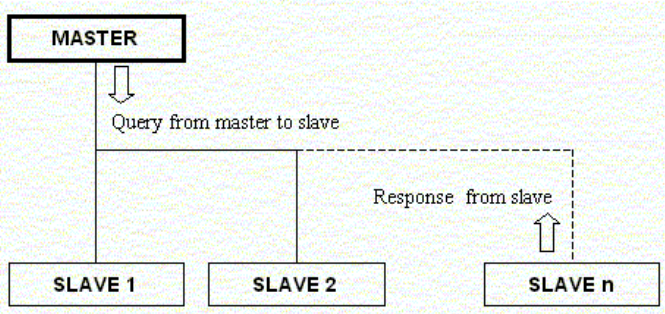

Fig.5 Simple example of Master-Slave control system chain

B. *Distributed Control Systems*

A Distributed Control System (DCS) is made up of several CPU-based control units that are physically distributed across a system, linked by a communication bus, and appear to the end user as a single system [44]. Distributed systems have been evolving rapidly over the last 30 years because of the ongoing advances in network communication and have become more common in large system control as a result. The multiple CPUs present in a DCS allow for higher performance bythe system, while the network maintains the single system transparency. Each CPU within a DCS is commonly referred to as a node; each node has its own kernels for handling all local resources and interprocessor communications [45]. Fig. 6 is a graphical representation of a decentralised DCS.

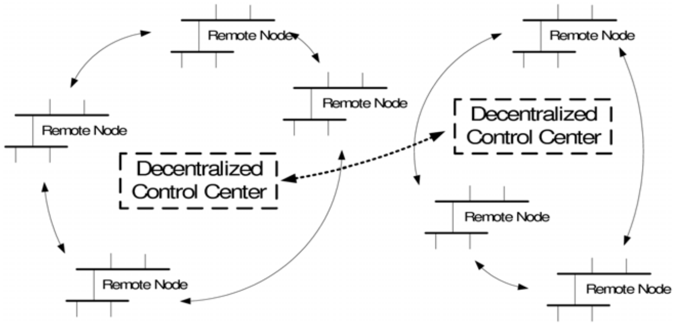

Fig.6 Simple example of a decentralised Distributed Control System

As ocean energy converters will likely be set up in small and large farms similar to how wind energy converters are used, the single transparency of multiple processing units of DCS make it an excellent fit for the control requirements of a farm of energy converters. DCS has proven successful in a myriad of electric power distributed generation systems, including isolated wind systems [46, 47]. Work conducted in [48] concluded that it is unlikely that typical MS control systems will be able to handle large numbers of small intelligent generating units such as the WEC systems proposed in this paper.

V. CONCLUSIONS

As wave energy continues to approach commercial viability, the need for comprehensive RTIMCS development becomes more important for more than simple PTO control. System condition monitoring and the sharing of informationbetween devices as well as outside system will be paramount to the eventual success of ocean energy conversion systems. The constant advances in fields including condition monitoringsensors, wave monitoring and forecasting, control system schemes, and smart grid infrastructure and design should be considered as the RTIMCS for WECs develop into commercialgrade, and this paper hopes to help foster that development.

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